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Article

Virtual Reality Application of Lathe Machine Training

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Abstract. This study aims to utilize Virtual Reality (VR) technology to develop an industrial training application with content focusing on Machining operation using lathe machine. The focus of the study is to present the content being taught in manufacturing laboratory classes about lathe machining operations in the virtual world. Machining operations demonstrated within this application includes turning, facing, chamfering, cutoff, internal and external threading. The user journey is designed to guide users through the content tailored aimed to familiarize them with the order of operation and safety guidelines. This educational tool further provides the freedom of the user to repeat the process without restriction to their location, time, or resource, as opposed to conventional hands-on laboratory. The study involves the research of the laboratory content, development planning, assets creation, functional design and implementation, and integration with Salesforce platform as learning assessment database tool. This study emphasizes future content expansion and is therefore developed with modularity in mind to best promote future content enrichment. The application resulted in the ability to represent a total of 5 machining operations.

Keywords: Virtual reality, virtual education, machining.

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1. Introduction

This research covers the development of a Virtual Reality (VR) software capable of the hands-on laboratory classes involving the lathe machining process. This will be achieved through the development of a VR software containing the key academic concepts taught during traditional lathe machining workshop classes. Conveyed via a virtual reality headset and controllers, the content available will allow the user to interact with and inspect the workshop environment, modeled after the real world, where a series of tooltips will appear to guide the user. Once the user is more confident, they will be allowed to go through the steps of the workshop on their own to test their skills. With the software containing the information taught during a class, hands-on lathe machining laboratories could be made more accessible than ever before.

With the impact that SARS-CoV-2 has had over the health and societal perspective of the global community, it is beneficial to explore and design a new way students can undergo machining laboratory training. With in-person communication and interaction posing health risks, advised against by healthcare authorities, and prohibited by law in certain circumstances, measures should be taken to increase the capability of off-site learning [1].

Traditional machining workshop classes are typically separated into 2 main parts; the first where the students are lectured over the main principles governing the phenomenon involved in the machining process and the machines involved, and the second where the students are dealt with a series of tasks to be completed. Normally the workshop part shall involve the students operating a lathe machine to perform various cutting processes. However, with the social distancing, travel and gathering restrictions, and education institute closure measures, students are not able to attend these workshops in-person. While online lecture classes may be conducted to a level of efficiency comparable to in-person lecture sessions, workshop classes may never be fully replicated via a conference or recorded video material.

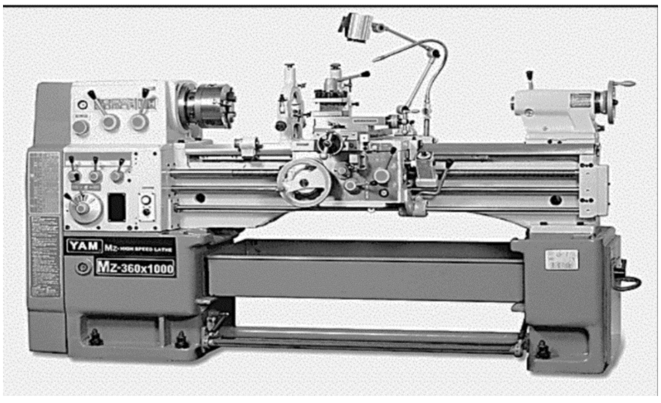


Fig. 1. Lathe Machine [2].

A typical lathe machine is shown in Fig. 1 to provide context. In order to provide the students with proper understanding of how the lathe machine is operated efficiently and safely, the medium must be able to provide both theoretical understanding and practical proficiency to the student. To achieve this, virtual reality software is ideal, as it can allow the user to explore the processes from various angles, interact with the environments as if they are there in-person, and repeat the exercise as many times as needed.

Extended reality technology, a concept by which a simulated environment is processed and displayed to the user, and virtual reality is a subset of that. While extended reality is an umbrella term which includes Virtual Reality (VR), Augmented Reality (AR), and Mixed Reality (MR), whose differences shall be explored in further detail, the scope of this paper shall focus on the impact and application with which Virtual Reality can enhance the machine operation workshop class experience. Virtual Reality is distinguished from the other technologies that, while Augmented Reality and Mixed Reality display the content to the user overlaid on the real world, Virtual Reality displays the content via a headset, which is positioned at the front of their face, by which the users' field of vision is completely isolated from the real world. Extended reality systems with the display device attached to their face without needing the user to manually hold the device to view the content frees the user's hands to use the controller to interact with content. There are two main principles that govern the way users interact with their Virtual Reality systems: hand-held controllers and camera-based hand tracking. It is widely accepted that Virtual Reality systems are more suited to educational applications than Augmented Reality and Mixed Reality systems, particularly if the content involves extensive visual presentation and interaction [3].

A Virtual Reality system, traditionally speaking, consists of 2 main hardware components, the headset and the controller. The headset is a graphics rendering device which is strapped on the user's head, while also providing a tracking capability, meaning that the content's viewport displayed to the user is dynamically updated in real time based on the position and rotation of the headset. This allows the user to navigate and experience the scene of the content as if they were in that environment in-person. The second part of the Virtual Reality system is the input capturing device, typically a hand-held controller which offers both positional and rotational tracking as well as multiple buttons for the user to press. While camera-based hand tracking technology is being developed at an accelerated rate, the hand-held controller method of input remains as the more accurate and reliable design approach. While the first wave of virtual reality systems has been introduced since the 1960s, with many aspects of their implementation constantly researched, improved and reviewed [4], the majority perception of the public still perceive its usage as limited to the entertainment and video game industries [5]. These perceptions are most likely an effect of the earlier applications of the technology being overwhelmingly short-form entertainment with very limited business usage. The improvement as an effect of constant research and development of the software and hardware powering the newer waves of reality systems, however, are poised to eventually overcome these social perception shortcomings. With the most recent Virtual Reality systems' hardware, the processing power of the processor allows for more advanced computing and more immersive graphics to be shown to the user. Meanwhile, more accurate headset and controller tracking allows for the user to feel more immersed and for the content designer to simulate a more realistic user interaction. Despite the advancements, in consideration to current consumer-grade hardware limitations, this VR application does not aim to assist the users in the development of a realistic hand skill improvement and is aimed to supplement the workshop classes and familiarize the user with the steps of the lathe machine operation rather than the motor skills related to the operation.

VR has been implemented in applications such as real-estate development industries, where the clients are able to experience the design and the space being offered by the real-estate agent or interior designer without the need to actually create it and provide a tour experience for the clients, reducing the cost of marketing in these industries. Industrial plant designers have used VR softwares to illustrate and experience their design before actual implementation, providing the sense of scale, which is otherwise not able to be conveyed through any other types of media. VR has also been implemented into the educational sector, by which training for specific and difficult to replicate situations are enabled by VR softwares, which allows for the user to conduct the training in a contained and safe environment [6], enabling the user to absorb as much information as required, particularly graphical cues.

Regarding how VR enables an immersive and effective educational experience, the technological and pedagogical reasoning can be summarized into 3 main aspects. Firstly, the fact that the headset blocks the field of vision of the user and helps facilitate the sense of presence helps focus the user's attention to the content and minimize distractions and allow the user to experience the environment, rather than observing. Secondly, the ability of tracking the movement of the controller and headset, and by extension, the hand and body, allows for the user to familiarize with their surroundings and components relevant to the operation, reducing time between task assignment and execution, which may be crucial in time-sensitive tasks. Lastly, the repeatability and the predictable nature of an e-learning content means that users with differing learning capability are able to "go at their own speed" and repeat the content as much as required to ensure a deep understanding of the learning material is achieved [6].

Fig. 2. VR Lathe by Mechatraining Ltd. [7].

In a product of training software developed by Mechatraining Ltd., the user is able to operate a lathe machine and operate a pre-programmed turning operation [7]. In this software, the user operates a lathe machine and is tasked with the setting up of the lathe machine, including the alignment of the tailstock, turning on the machine, aligning the cutting tool. This offers the user a way to familiarize themselves with the steps of a turning machine operation. A sample screenshot can be found in Fig. 2, where the user can be seen operating the lathing machine. However, what this research aims to improve on is the addition of informative tool tips for each interactable components and the addition of preliminary demonstrative stage, where the user is allowed to learn at their own pace and eased into the understanding. This research also aims to allow the implementation of other machining operations, including facing and tapping.

While this implementation by Mechatraining Ltd. has proven that implementing a dynamic turning operation simulation within a VR medium is indeed possible in the commercial sense, this research aims to build further on that and aim towards education, with more emphasis on university students as the focus group as well as integration with a scoring and remote completion tracking system with the integration of Salesforce platform integration. Additionally, this research aims to create a system which allows for an easily customized content. This is highlighted by the goal in implementing an "assessment" stage, a stage where the user is tasked with completing the operation with minimal guidance, all while the system tracks the correctness and safety of the steps of operation. This allows the application to educate, validate, and assess the learning criteria as required by the curriculum of the Manufacturing Process Laboratory course this application seeks to accommodate. Therefore, to fulfill that requirement the "assess" mode of the application shall allow the validation, tracking, and reporting of the performance of the user. This involves the requirement of the assessment report to be sent electronically to the course instructor which will allow for a dynamic performance tracking, which is required as part of the course's learning criteria involves the assessment of the students' ability in performing the machining task safely and efficiently.

2. Addressing the Challenges

2.1. Effectiveness of Online Media

While off-site education allows students to continue their education functions and increase their understanding in their respective fields of study during a global pandemic, it must be addressed that the effectiveness of traditional media directly translated into online media can yield suboptimal results. Certain objectives of learning, such as lecture classes can be achieved via online learning, and in some cases, be more effective than on-site learning. However, hands-on learning and lessons that require live demonstration and practices do not translate well easily. Therefore, it is beneficial to effectively utilize the available technology to migrate educational content involving complex machine operation demonstration and practicing onto a VR media, which is demonstrably more effective in equipping the learner with applicable skills and understanding of the field than the utilization of pre-recorded demonstration videos of a process being performed, which, while a great substitute when no on-site class may be performed, loses the ability for the learners to interact with the actual objects and apply their knowledge in performing the operations.

2.2. Healthcare Concerns Regarding On-site Learning

There are various way that the SARS-CoV-2 pandemic has impacted the way our society functions, while measures to limit the effect have been put in place, it is crucial that numerous substitutes of activities that require person-to-person interaction should be researched and implemented. Should the number of activities entailing in-person presence be reduced, future healthcare concerns or other circumstances limiting attendance of students would not negatively impact the capabilities of which students can learn as much as it has been. If we are able to implement online education effectively and readily accessible to all, the educational system will be much less vulnerable to unforeseen disruptions such as the one that was seen in recent years.

2.3. Sustainability and Environmental Impact

The impact of climate change becomes more apparent in all capacity of the word; being resonated by climate researchers across the world, shown through more drastic natural phenomena, and the global effort to reduce the impact of human activities on the environment. It is therefore crucial that we reduce the effect the education system has on the environment. While a transition to VR, a digital media, would naturally reduce paper waste typically generated through handouts and paper report submissions, the migration of machining workshops from the real world to the virtual world would also mean that we would limit the energy required to operate the machine, the material used to demonstrate and practice the machining process, and the wearing down of the machine used to conduct the workshop. With the system in place, we can achieve a more sustainable and environmentally conscious education.

2.4. Standard Practice and Learning Rate

As with all educational endeavors, the human factor is one of the central challenges faced in machine operation workshop classes. Firstly, while the teaching material can be standardized and optimized, it is not possible to replicate the details of the explanation in the same way. Secondly, it is not possible for all students to learn at the exact same rate. Finally, it is not possible for traditional recorded media to allow the student to have the opportunity to exercise and experience the operation. In the case of an emergency, having the muscle memory of how the appropriate action needs to be performed can make all the difference. Having accounted for that, it can be said that the safety of machining operation depends greatly on whether the user has experience hands-on training of the craft or not.

3. VR Technology and Current Hardware Market

VR is a technology which takes advantage of the various advancements in computing, graphics processing, motion capture, and display technologies to achieve the goal of immersing people in a computerized environment [4]. The technology achieves this with 3 main components: the graphical output device, computing unit, and user-control device. Firstly, the graphical output device, typically in the form of a headset, is a device which is mounted over the user's face and displays the graphical output while capturing the position and rotation of the user's head. Secondly, the computing unit processes the information from the various user input devices and computes the appropriate output to be displayed to the user. Lastly, the user-control interface device is responsible for capturing the user input, in the form of the movement of the controllers themselves and button input and enables the user to interact with the content.

Many of the VR systems available to the market conform to this convention, with the examples ranging from the Valve Index to the Oculus Rift, to the HTC Vive. These VR systems utilize a personal computer as the computing unit. which interfaces with the headset and controllers either wired or wirelessly. An exception to this convention are the mobile-phone powered VR solutions, which typically forgo the usage of controllers and capture the user's input via the device's integrated touchscreen. Another exception, in the form of stand-alone VR systems such as the Oculus Quest line of products, integrates the computing unit within the headset itself, enabling the power of VR without relying on a personal computer.

The technology involving immersing users within a digitally processed "reality" to convey information to the user in an isolated environment has been in public awareness since the 1960s [4]. Therefore, the majority of the features and potential applications the technology can offer to the market has been largely explored, implemented, and validated. Such research has been conducted by Baceviciute [6] and Miles-Novelo [8] where significant improvement over traditional media can be attributed to the use of VR as a medium for conveying key visual and auditory information for the usage of education and training.

In regard to the impact this has to this research paper, it is best to relate back to the current capabilities of the current hardware, as well as the trend of the hardware market. When developing a software package, the designer must consider which sets of hardware would be supported or to be focused on. Therefore, it is a good idea to now break down the options available to be used as a target of this research.

The VR application of this research would require extensive user input capturing capability; therefore, it is decided that mobile phone-powered VR systems not be the main target of implementation due to the limited user input. Additionally, one of the aims of this implementation of VR application is to increase the accessibility and availability of machine workshop training. For this reason, a standard VR system which requires an external computing unit, in the form of a personal computer or laptop, is not preferred, as this introduces additional cost of entry for the implementation. In addition to that, the requirement for a computing unit reduces the effectiveness this research may have in terms of mitigating the effect a pandemic may have on the training and education process. On the other hand, the current standalone VR system in the market, for example, the Oculus Quest, offers a relatively cheap capital cost, improved implementation flexibility, and better accessibility to a wider market.

The current VR systems offered in the market can also be segmented via the method by which the user's input is captured; the outside-in tracking and the inside-out tracking. Each of the methodologies offer different advantages, it is therefore beneficial to try and analyze which types of VR device is better suited for this application. The outside-in tracking system offers improved tracking accuracy and latency performance, making the response the user experiences within the software more life-like, improving immersion, and promoting information absorption of information. Meanwhile, the inside-out tracking system offers better flexibility and the ability to start up the system and undergo training wherever and whenever. Fortunately, the research paper aims to develop the software under the Unity XR tech stack, which provides excellent compatibility, as shown in Fig. 3, meaning that this research does not need to choose or prioritize developing for one method of tracking for the other.

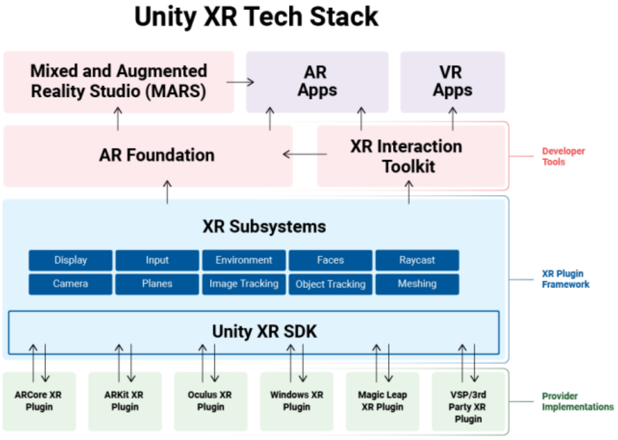


Fig. 3. Unity XR Tech Stack [12].

3.1. VR versus AR in Training Context

While both VR and AR both hold different advantages over the other in different scenarios, visually demanding tasks and training with extensive interaction requires first and foremost focus from the user to be effective [3]. VR offers this first aspect with its ability to isolate the user's field of view entirely from their surroundings and displaying the relevant content to the user. This is an important leverage which can promote superior learning experience for the user, as the designer can guide the user's vision to the part which is deemed important at any particular point in time. AR, while superior in displaying the content in the context of the real world, lacks in this regard, as the designer can never foresee in which environment the content will be displayed in, making it challenging to maintain consistency in delivering the optimal learning experience. It is therefore concluded that, in terms of cognitive experience, VR offers a superior platform by which contents can be presented to the user with concision and focus.

Another important factor to consider in the implementation of a digital media in education and training context is the interactivity of the content [3][6]. While effectiveness of theoretically focused content may not require extensive intractability, training focused content, particularly one which requires the user to perform a series of tasks to achieve a series of goals, can improve dramatically with increased intractability. VR, particularly in systems with dedicated hand-held controllers, offer superior interaction capability to the user as opposed to a point-and-click interaction capable in AR-based applications.

Another shortcoming facing the current and future endeavor of providing industrial training to students is in regards to availability. Traditionally schools without the actual equipment to teach students may not be able to offer lathe machine operation at all. With the introduction of digital media, however, students can experience the training regardless of their ability to gain access to the machine. AR, in this regard, trumps over VR due to the former's ability to be accessed through mobile phones alone. A survey by the National Statistical Office of Thailand in 2020 reported that 86.4% of the population over the age of 6 has access to smartphone devices [9]. In contrast an estimate reports a number 20 million headsets sales globally, only accounting for 0.25% of the population [10]. It is, however, estimated in May of 2021 that more than 5 million units of Oculus Quest 2, a standalone VR headset has been sold just 6 months after its launch in October 2020 [11]. It is therefore plausible that VR headsets be more accessible and available for all users, particularly after the announcement by Meta, the global player in the market that they intend to invest no less than $10 billion in the coming years, to reduce the cost of headsets, possibly enabling hundreds of millions of people to gain access to VR.

4. Machining Process in Manufacturing

As part of a Manufacturing Process Laboratory course, students are required to undergo training with the operation of a lathing machine. A lathe machine is a manufacturing machinery responsible for the process of turning, a category of traditional machining process which involves the removal of material of a rotating workpiece using a cutting tool fed linearly. A typical turning process is illustrated for easy understanding in Fig. 4(a) [12]. Furthermore, the various operations capable by a lathe machine includes turning, facing, boring, drilling, cutting off, threading, knurling, profiling, and grooving. Some of these operations are illustrated in Fig. 4(b).

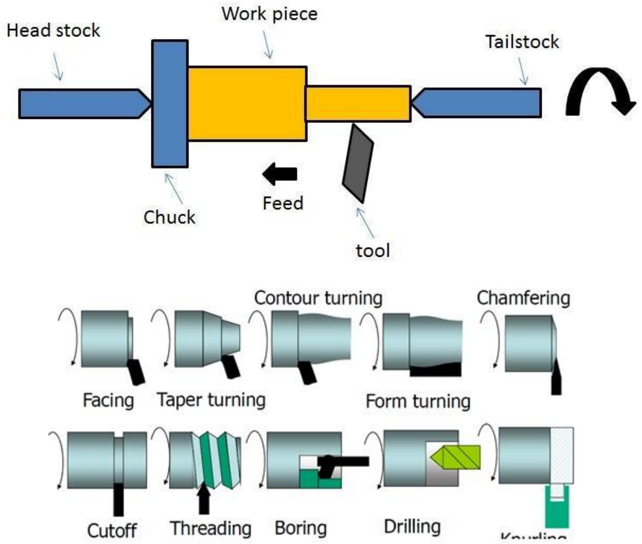


Fig. 4. (a) Diagram of a typical operation using a lathe machine [12]; (b) Examples of various operations available on a lathe machine [13].

As described by the course material on the Manufacturing Process Laboratory (2104258) class covering the machining lab, to further a student's ability to operate the lathe machine safely and correctly, a series of exercises should be followed, covering; turning, facing, chamfering, and drilling [2].

To further explore how the machining process works, it is helpful to first determine how the material removal process is achieved. A detailed illustration of the various components of a lathe machine provides an excellent can be seen in Fig. 5 . In a turning operation, the chuck tightly holds the workpiece, providing the friction force necessary to fix the workpiece to spindle. Then, the tailstock is positioned at the opposite end of the workpiece to help better secure the workpiece during operation, operated using a handwheel crank. This step can be forgone during certain lathe operations which require material removal at the other end, such as drilling and boring. Once the stability and position of the workpiece is adequate, the cutting tool shall be set-up with the adequate cutting geometry, parameters of the cutting tool relative to the workpiece, which will govern the characteristics and the results of the operation. Once all components are set-up, the spindle will be driven to rotate at an adequate speed, while the cutting tool will be fed into the workpiece in the longitudinal. This process can be repeated many times until the desired geometry of the workpiece is achieved.

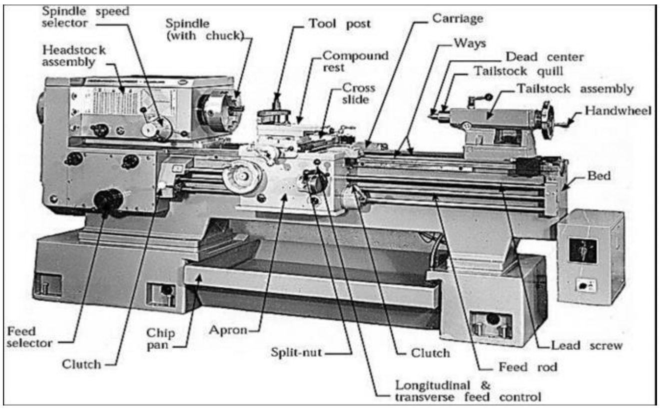


Fig. 5. Detailed component breakdown of a lathe machine [2].

In regard to the mechanism by which the material is removed from the workpiece, it is achieved through the force of impact between the cutting tool edge and the workpiece's material. When the shearing force of the cut exceeds the bonding energy between the material's molecular structure, the material separates, creating a cut. The removed material, typically called "chip", is formed in different forms, depending on the cutting parameters and the properties of the workpiece material. There are 2 main distinguishing types of chips in a machining operation, either discontinuous chip, where the removed material is broken down into smaller pieces, and continuous chip, where the removed material takes a ribbon-like string. For the purpose of efficiency of the operation, discontinuous chips are preferred, as continuous chips may become tangled with the moving parts during operation, which can force a halt to the machining process. To promote discontinuous chips, the appropriate cutting tool and cutting parameters should be selected. It is proposed that the integration of force sensors in a CNC turning operation to predict chip formation during a cutting process and utilizes a Neural Network to process the output signal to provide real-time response to optimize the cutting parameters [14]. Although, for the purpose of this research, a manually controlled lathe machine may not benefit as much operational efficiency increase as an integration to a CNC turning machine.

5. VR Application Development Framework

Considering the abundance of external resources and the widespread community of developers available for support, Unity, a game engine software, is an ideal choice for developing a VR software. Unity is a game engine which supports and is a base of several mainstream video games in the market and offers a free license for personal use and small organizations, promoting a big community of developers with several tools available which can shorten the software development time. The size of the community also provides a source of information by which new developers are able to learn and gain technical support where other proprietary software development frameworks may lack. Most importantly, Unity offers a robust and versatile development framework for Extended Reality applications and offers a wide range of compatibility and tools for developing a VR application.

As discussed previously, the increasing market share of both Oculus headsets as a whole, and more particularly the Oculus Quest line of products, which includes both base station-reliant outside-in tracked VR system and standalone VR headset which relies on inside-out tracking system, means that a development framework which offers greater compatibility should eliminate or at least dramatically reduce the development time entailed by the requirement to implement the same software package on multiple hardware platform. For the purpose of this research, it is therefore an unavoidable advantage that the Unity Extended Reality Development Framework offers that is too convincing to pass up on.

Now, in regards as to the development process surrounding the design and implementation of a VR application using the Unity game engine shall be discussed in detail, ranging from; the tools the Unity game engine software offers to the developer, the configurability and the packaged tools given to the developer to design complex interactions and application-specific functions that can be accelerated through the various tools offered by the Unity community and pre-packaged tools.

5.1. Software Development Tools

The following tools shall be used during the software development conducted for this research; Unity 3D game engine, 3D modeling software, VR system, and a Feature Driven development method.

Firstly, Unity 3D game engine is the framework which shall be used to compose the scenes, design and implement logic, and packaging the software within its Extended Reality framework. The ability to easily compose the scenes easily with an intuitive interface allows Unity to be both efficient and easy to understand. Meanwhile, the ability to implement any extra functionality not pre-configured with the game engine using C# programming language means that the research will be able to implement the logic required to replicate the interaction between objects of a machining process. This is especially true due to the extensive capability and flexibility of the C# programming language. Perhaps, most importantly, the unrivaled compatibility offered by the Extended Reality framework of Unity means that, for most cases, the developer would not be required to repeat the design process for VR headsets with different operating systems.

Secondly, Blender shall be the prime candidate for the 3D modeling software, due to its open-source nature and a combined documentation and tutorial creation effort by the software provider and the users. Firstly, the fact that it is a free software means that there are a multitude of tools created by the community of users which can accommodate and automate certain tedious works, which can alleviate some of the development problems which may be encountered during the process. Secondly, the extensive pool of documentation and tutorials created and available for free for the users to research means that there is almost always an answer to any of the questions a person may encounter while using the software. The extensive support offered ensures that no roadblock should arise from the solid modeling effort conducted during this research.

Thirdly, having a VR system on-hand during the development process would ensure a constant testing regime can be conducted, which would enhance the effectiveness of the Feature Driven methodology, which will be detailed below. Essentially, having the ability to test the functionality of the software during the development reduces the chance of the developer encountering any difficult mis-designs. To expand on this reasoning, imagining the opposite situation should be sufficient. Suppose the developer does not possess a VR system at all times, the developer would not be able to verify whether the recent component, which was designed works as an isolated case, whether it works once it meshes with the other existing components, and whether the performance of the system is extensively hindered due to the recent changes made.

Lastly, the development method which shall be used to govern the majority of the software development is the Feature Driven methodology, which offers great advantages over other Agile development. The Feature Driven method involves an incremental development process and constant testing of software capability to ensure a correct business logic is implemented and the developer does not become confused with the goal of the development. The method also allows delivering tangible and verifiable results more constantly. While this methodology was originally intended to increase the scalability of a long-term development project, incorporating the method alongside an Agile framework allows the method to thrive for a focused and specific software development endeavor. This is foreseen to be especially required as to ensure a successful and efficient business logic is implemented in an effective manner in terms of both development time and user experience. This effectiveness can be further compounded with a builder programming pattern, which takes advantage of utilizing common code or functions where possible in order to ensure both reduced development time and makes modifications of existing behaviors less difficult.

5.2. Business Logic Implementation

The logic design implemented in Unity 3D game engine can be broken down into 4 main parts: User input, user input context, system object interaction, and custom logic. The flow of information is shown in Fig. 6. Firstly, the user input capture is responsible for capturing the headset and controller. Secondly, the user input is contextualized to allow the user input to be understood in the system context. Thirdly, the system object interaction allows the user input to target specific game object within the scene. Lastly, the system interaction must trigger a specific custom logic to produce the desired result.

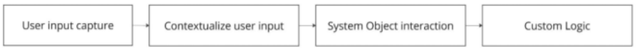


Fig. 6. Breakdown of logic implemented within Unity 3D game engine.

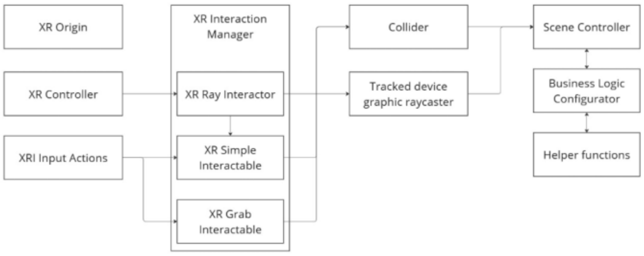


Fig. 7. Breakdown of information flow focused on user interaction and how it affects the business flow.

User input capture is implemented using XR Origin, XR Controller, and XRI Input Actions. XR Origin is responsible for capturing the translation and rotation of the VR headset, XR Controller is responsible for capturing translation and rotation of the VR controllers, and the XRI Input Actions is responsible for capturing interactions with the controller buttons. User input is then put into context by XR Interaction manager, which manages all user interactions from VR controls. XR Ray interactor helps guide the user interaction with objects from a distance. XR Simple interactable is used to capture user action with an object. XR Grab Interactable is used when an object should be grabbable by the user. To allow for each GameObject to be interacted with, collider and Tracked device graphic raycaster are used to identify the hitbox of 3D and 2D objects respectively. Lastly, the custom logic is controlled by the Scene Controller, Business Logic Configurator, and Helper Function. The scene controller is responsible for receiving the trigger captured from all of the interactable objects within the scene, allowing for a central control of all user interaction. The scene controller is also responsible for tracking the state transition of the scene. The Business Logic Configurator is used as the content management system, defining the order of user interaction the user is supposed to follow, along with the appropriate system action, which will then be executed by the Helper functions. This flow of information is visualized in Fig. 7.

In order to re-create the full experience of a machining working experience, the program package must implement the appropriate functional linking between the objects as well as the physical interaction to replicate the real-world behavior of the objects. For instance, in order to replicate the process by which the cutting tool causes the machined volume of the workpiece to be removed in the form of machined chips, a function that detects the collision between the solid mesh of the cutting tool and the workpiece volume must be created and implemented. The function must then output the overlapping volume and report to a separate function, which will dynamically modify the mesh of the workpiece. Implementing the logic of the interaction in this manner is computationally more expensive compared to a trick method, which measures the positional data of the cutting tool and modifies the mesh of the workpiece accordingly. However, the latter would not accurately capture the real-world physics of the machining process and would prevent the intended functionality of letting the user closely inspect the interaction of the rotating workpiece and the moving cutting tool. It is, therefore, preferable to consider the balance between the computationally efficient method of replicating the process or a method that is more closely related to the real-world phenomenon.

Therefore, the cutting functionality is to implement a simple way of representing the cutting of the workpiece. The workpiece, instead of a single game object with a single mesh, will be programmatically generated as a series of slices of cylindrical prisms, each with its own mesh stacked lengthwise. The slices are consistent in thickness but will vary in radius and their position among the workpiece length, as shown in Fig. 8. This method allows for the lathe cutting tool interaction with the workpiece to be computed with the standard Box Collider trigger detection, which is not computationally expensive. And thus, this method allows for the lathe cutting tool to dynamically interact with the workpiece along the lengthwise contact and end to end contact. In other words, this supports the turning, cut-off, and facing operation of the machining operation. This method is limited and unable to simulate drilling, chamfer, and boring operations and pre-made models will be required to support such operations which do not cut the workpiece lengthwise.

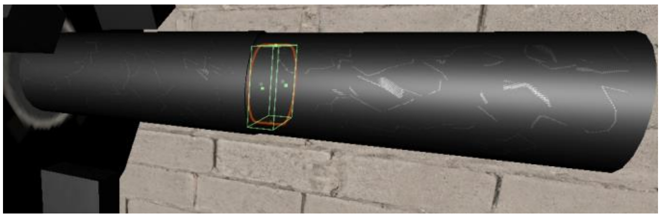


Fig. 8. A slice of the workpiece used to detect cutting tool contact.

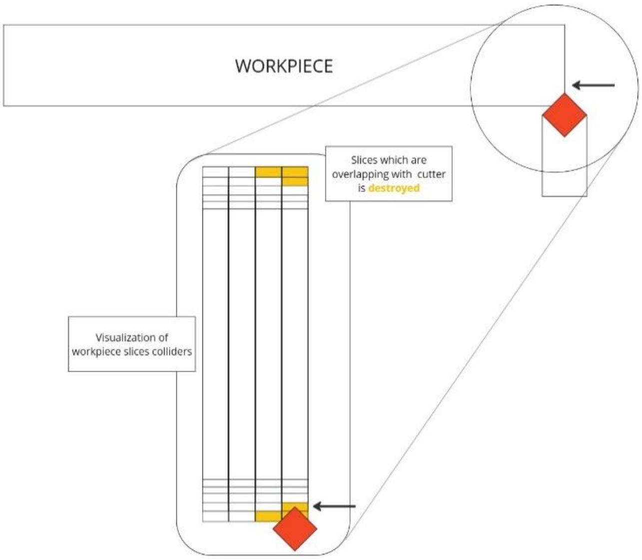


Fig. 9. Visualization of how cutting tool interaction with the workpiece is simulated.

To better visualize how the cutting tool interaction is simulated, refer to Fig. 9. Observing the workpiece from the side, it is created from a series of overlapping cylinders of varying diameter stacked on top of each other. In this example illustrated in the diagram above, 4 layers of workpiece slices are observed, with each layer consisting of 6 cylindrical slices, each with differing diameter.

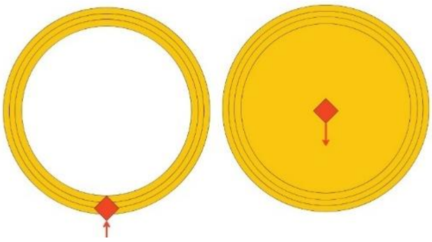


Fig. 10. (a) Cutting operation with tool being fed inwards; (b) Cutting operation with tool fed from center.

To visualize the limitation of the simulation method, refer to Fig. 10. With the cutting simulation logic relying on the collision detection between the workpiece slices and the cutting tool colliders, cutting operations from outside-in can be simulated without any issue. As the tool is gradually fed from the outmost slide in, the collider of the cutting tool first collides with the collider of the outmost slice, and as the tool is fed further inwards, the subsequent slices are then cut accordingly. However, referring to the figure on the right, suppose the tool is fed directly at the center, the collider of the cutting tool would collide with the collider of all slices at once, cutting all slices highlighted in orange. As such, operations which are not cut from the outside in are not suitable for this simulation method and are therefore needed to be simulated using pre-fabricated models.

While this approach exhibits limitations as described, the dynamic cutting simulation enables future developers to curate the content, add additional cutting plans, and vary workpiece results with minimal coding change. Future developers would only need to adjust the Business Logic Configuration parameters and only pre-fabricated 3D models of the workpieces resulting from operations not applicable to the simulation method must be prepared.

Aside from the object-object interaction, the user-interactable objects must also be linked with the appropriate trigger-action functions. For example, the speed controller of the lathe machine must correspond to the rotation of the workpiece. All of the parts of the lathe machine that must be operated by the user must also be interactable and configured to function in the same manner as their real-world counterparts. In regards to how these interactable objects shall be configured, the Unity 3D game engine offers an out of the box function to detect a user interaction, which can then flag other functions to operate accordingly. This function is versatile enough to cover most of the standard user interaction, such as pushing buttons. However, should an object require a more advanced user interaction, a function which governs and detects those interactions must be created. This process is heavily documented by the developer community and should not pose a challenge in this research endeavor. However, these custom functions should be carefully designed to minimize computational requirements as to reduce the inherent lag since the game engine may not be optimized for the function. This issue is not apparent for out of the box functions of the game engine, meaning that the software architecture is fully compatible and efficiently operates the function. This development gap can be minimized by carefully studying architecture and trying to take advantage of that.

As such the user interaction flow of information can be separated into 3 types, "Normal" objects where no special function is implemented or activated, "Controlling" objects where out of the box interaction detection function can be used to send over information onto other functions, and "Advanced" objects where standard interaction function cannot support and custom functions must be used to control the user interaction

In order to machine the workpiece, the user must complete the following major steps (Table 1). The user must first face the two ends of the workpiece to achieve the desired length, perform turning operation, apply chamfer, then apply threading with a tapping die. Each major steps include multiple minor steps, which are described in Table 3, 4, 5, 6, 7, and 8. Refer to Fig. 11 below to better understand the operations involved to machine the hammer handle workpiece.

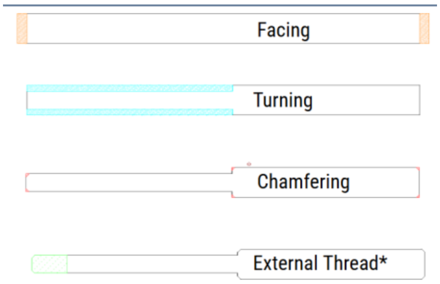


Fig. 11. Breakdown of the machining operations conducted on the hammer handle workpiece.

External thread operation is represented as an application of threading using a threading die instead of threading operation via a lathe machine. This is due to the cutting simulation method limitation as described previously. Due to the inability to actually cut the threading pattern along the length of the hammer handle workpiece, it is instead decided, that a threading die is to be used as the threading tool. Other operations, such as chamfering, despite using the pre-fabricated models to simulate the cutting operation, still remains aligned with the teaching content of a machining laboratory and is conducted via the lathe machine.

Table 1. Major steps required to machine hammer head.

Major Step	Execution	Detail (mm)
0	Perform facing operation at the end of the workpiece	Workpiece diameter: 16 Total length faced: 5 Rough cut increment: 1 Finishing cut increment: 0.5
1	Swap workpiece end	
2	Perform facing operation on the other end of the workpiece	
3	Perform turning operation to the shoulder a) Change tool b) Apply center drill c) Engage dead center d) Apply turning	Initial / Final diameter: 16 / 9.525 Turning length: 110 Rough cut increment: 0.75 Finishing cut increment: 0.2375
4	Perform 2 chamfer operations (1 on the end of the workpiece and 1 on the shoulder)	Chamfer spec: 1/16" x 45 deg
5	Swap workpiece end a) Disengage dead center b) Release chuck	
6	Perform 1 chamfer operation	Chamfer spec: 1/16" x 45 deg
7	Remove workpiece from machine	
8	Add threading to the handle workpiece using tapping die a) Prepare threading die b) Apply threading die	Threading specs: 3/8"-16 NC

Referring to Table 1 and Fig. 12, certain major steps require additional minor steps which are annotated to help distinguish the main purpose of the operation and the intrinsic required steps to support the operation. For example, in order to perform the turning operation in major step 3, the tool must first be changed in configuration in order to provide the appropriate cutting condition for turning. A center drill must then be used to accommodate the dead center which is used to secure the workpiece due to its long length during turning operation, and finally the turning operation is conducted. Another example is the major step 5, which is annotated in addition to its usual step to signify that the dead center must first be disengaged before the workpiece can be switched, but the disengagement of the dead center itself is not prominent enough to be considered a major step. Lastly, the major step 8 is annotated into 2 parts, which include the stage at which the workpiece is not yet threaded and the final result.

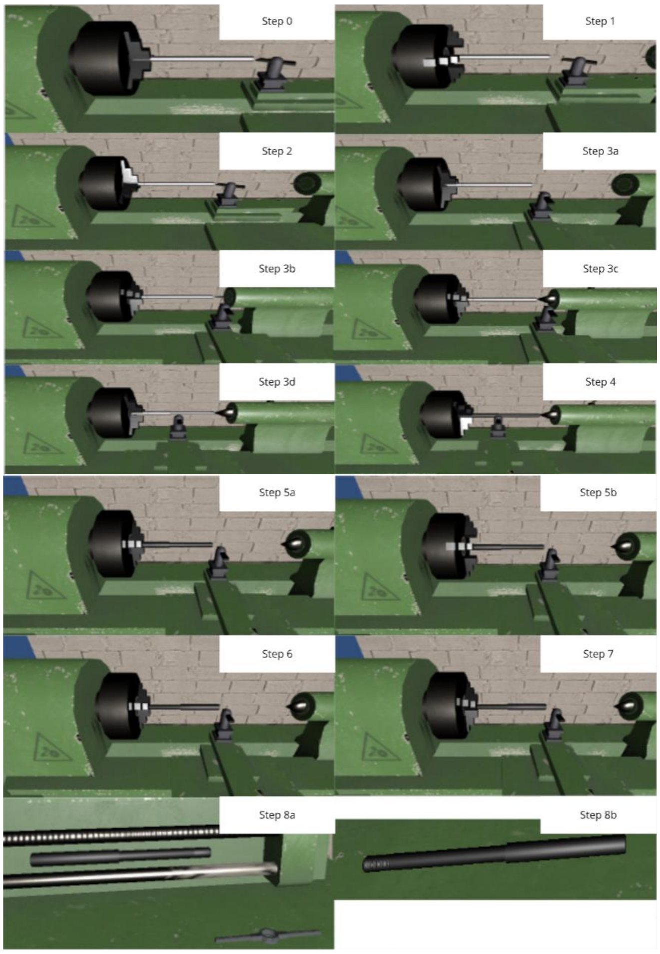


Fig 12: Major steps required to machine hammer handle

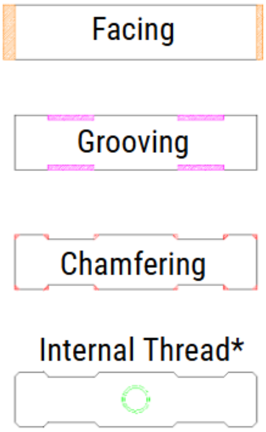


Fig. 13. Breakdown of machining operations conducted on the hammer head workpiece.

As for the hammer head workpiece ,the user must complete the following major steps (Table 2). The user must first face the two ends of the workpiece to achieve the desired length, perform grooving operation, apply chamfer, drill the hole to the side of the workpiece and apply threading with a drill press. Each major step includes multiple minor steps, which are described in Table 3, 4, 5, 7, 8, and 9. Refer to Fig. 13 below to better understand the operations involved to machine the hammer head workpiece.

Table 2. Major steps required to machine hammer head.

Major Step	Execution	Detail (mm)
0	Perform facing operation	Workpiece diameter: 19 Total length faced: 4 Rough cut increment: 1 Finishing cut increment: 0.5
1	Swap workpiece end	
2	Perform facing operation on the other end of the workpiece	
3	Perform grooving operation a) Change tool b) Apply grooving	Groove width: 16 Groove depth: 1.5875
4	Swap workpiece end	
5	Perform grooving operation	
6	Perform 3 chamfer operations	Chamfer spec: 1/16" x 45 deg
7	Swap workpiece end	
8	Perform chamfer operations on the remaining corners	Chamfer spec: 1/16" x 45 deg
9	Remove workpiece from machine and move to drill press	
10	Drill hole on workpiece and apply threading using threading tool	Threading specs: 3/8"-16 NC

Table 3. Execution steps to face the end of a workpiece.

Step	Execution
0	Interact with carriage to move tool to initial position
1	Interact with cross slide to move tool to initial position
2	Interact with the lathe machine to turn on the lathe machine (and set the spindle speed)
3	Interact with cross slide to face the end

Table 4. Execution steps to swap a workpiece.

Step	Execution
0	Interact with the lathe machine to stop the spindle
1	Interact with carriage to move tool away
2	Interact with cross slide to move tool away
3	Interact with the chuck to release the workpiece
4	Interact with the workpiece to switch the workpiece (or end)
5	Interact with the chuck to secure the workpiece

Similarly to the annotation used in hammer head step visualization in Table 2 and Fig. 14, the major step 3 is also annotated with 2 parts, first is to change the cutting tool to a grooving tool and the operation to perform the grooving itself.

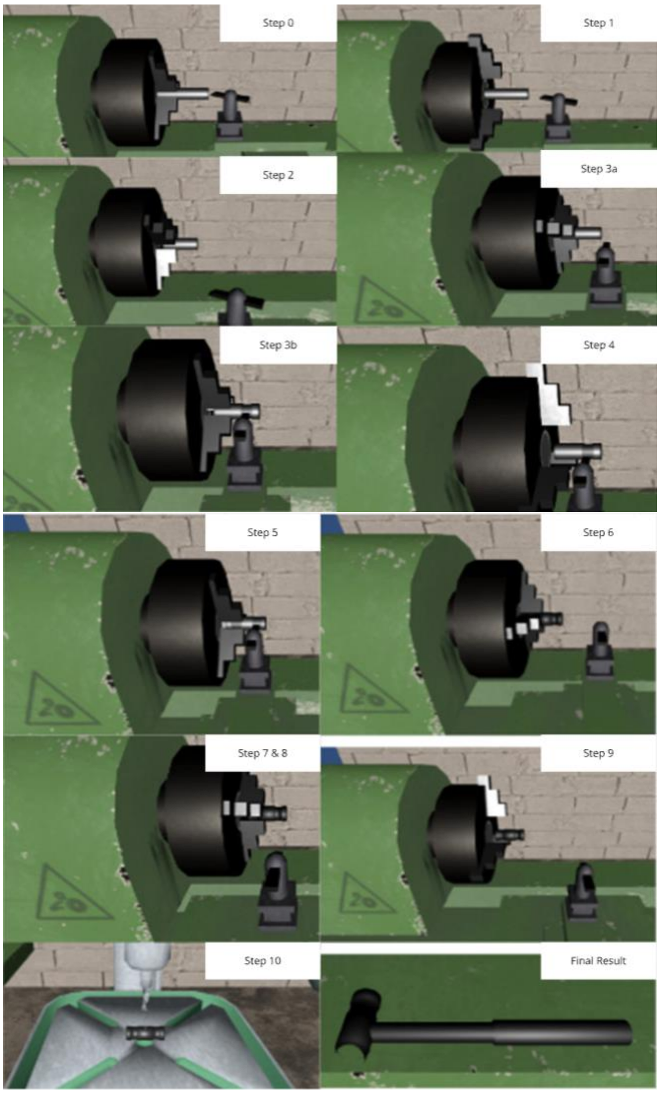


Fig. 14. Major steps required to machine hammer head.

Next to achieve the desired shape, the user must turn the workpiece shoulder, the user must first interact with the tools to execute the following steps (Table 5) to change the tool, after which the user is able to perform the turning operation (Table 6).

Table 5. Execution steps to change lathe machine tool.

Step	Execution
0	Interact with carriage to move tool away
1	Interact with cross slide to move tool away
2	Interact with the tool post to change the tool

Table 6. Execution steps to perform turning operation.

Step	Execution
0	Interact with carriage to move tool to initial position
1	Interact with cross slide to move tool to initial position
2	Interact with carriage to perform turning operation
3	Interact with the lathe machine to stop the spindle

Table 7. Execution steps to perform chamfer operation
.

Step	Execution
0	Interact with carriage to move tool away
1	Interact with cross slide to move tool away
2	Interact with the tool post to change the tool

Table 8. Execution steps to apply threading to the workpiece.

Step	Execution
0	Interact with the threading tool to prepare and attach the tool to the workpiece
1	Interact with the attached threading tool to perform threading
2	Interact with the threading tool to remove the tool from the workpiece

Table 9. Execution steps to drill and apply threading with drill press.

Step	Execution
0	Interact with drill press to drill initial hole
1	Interact with threading tap to switch drill tool on drill press
2	Interact with drill press to apply threading

Miscellaneous steps which include using the lathe drill to drill the center hole ahead of engaging the dead center, engaging and disengaging the dead center before and after the turning operation, and assembling the workpiece handle and head are described in Table 11, 12, 13, and 14 respectively.

Table 10. Execution steps to perform center drilling to accommodate dead center.

Step	Execution
0	Interact with tailstock to move tailstock towards the workpiece
1	Interact with tailstock to feed center drill towards the workpiece

Table 11. Execution steps to engage dead center to secure workpiece.

Step	Execution
0	Interact with tailstock to switch out center drill for dead center
1	Interact with tailstock to engage dead center with workpiece

Table 12. Execution step to disengage dead center ahead of releasing chuck.

Step	Execution
0	Interact with tailstock to move tailstock away from the workpiece

Table 13. Execution step to assemble the workpieces together.

Step	Execution
0	Interact with hammer head workpiece to move it to the lathe station
1	Interact with hammer workpieces to assemble the hammer handle and head together

5.3. 3D Modeling Method

There are multiple methods available in the field for creating 3D models which utilize different kinds of techniques. Comparing a standalone VR hardware with a computer running with high performing GPU, its computational power in rendering 3D objects is far inferior, restricting the number of polygons present in the scene. With this limitation, the 3D objects used for VR software development are often created from a simple shape. The suitable method for this research is box modeling where the modeling technique starts from a basic shape (such as a cube, a cylinder, or a sphere) and expands further until the final shape is acquired. On Blender, box modeling is considered one of the fundamental methods which allow the designer to get familiarized quickly and produce great results.

However, no matter how good the final 3D models look, they are not visually appealing or considered realistic enough as the model has no texture or perceptive depth that resembles real objects. The created 3D objects must undergo a texturing process which adds a textured finishing and creates a realistic visualization. In order to create a realistic virtual scene, with a realistic atmosphere, these methods are crucial for achieving the best result. With these hardware limitations in mind, it is fruitful to try and avoid going into the uncanny valley, a phenomenon used to explain the negative impression a human mind can have on a computer graphics object which is designed to look realistic, but is not entirely immersive enough for it to be believable. Due to the hardware limitation, this means trying to achieve photorealism in VR is almost impossible, it is therefore recommended that textures be used to complement the aesthetics of the software rather than trying to emulate the real-life counterparts.

5.4. User Workflow

With the main focus of this research being the implementation of VR-based content to replicate and potentially replace the traditional in-person teaching and training sessions of a machining workshop using a lathe machine, it is important to put an emphasis on the designed flow by which the users are expected to follow, by which the content can be designed surrounding that flow to guide the user.

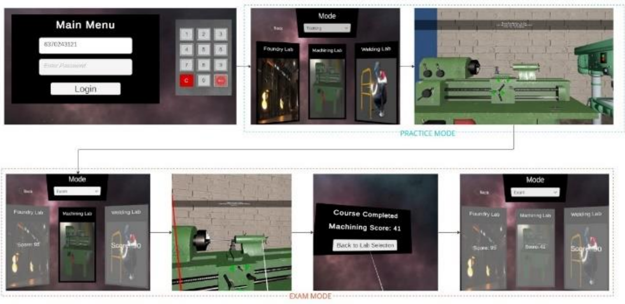


Fig. 15. User Workflow within the VR Application.

Following the flow provided in Fig. 15, the user starts up the application and fills in their credentials in order to allow recording their attendance and status of their assessment completion. Once the application starts up, the user will enter the Home page, showing a list of menus to navigate the application, from here, the user is able to enter the Tutorial mode, Assessment mode, or Help menu. Within the Help menu, the user will be presented with the basic controls mechanics of a VR application, intended to educate users who may not be familiar with VR experience. Once the user selects the tutorial mode, they will be presented with a brief introductory pop-up containing the background information of the machining operation. Once the user proceeds, the user will be guided by a series of informative pop-ups along with a "ghost" performing the setting-up task of the lathe machine operation, including the powering up of the machine, setting up the workpiece onto the chuck, installing the cutting tool, and setting up the alignment of the tailstock. After that, the operation of the lathe machine will be demonstrated by the ghost, coupled by a series of explanations to guide the user on the reasoning of each of the steps. This applicatory demonstration nature ensures that the user is able to associate the goal of each sub-task with each of the steps being performed. This allows for the user to understand the reasoning of each of the steps, allowing them to map the desired outcome with the necessary steps when they are required to perform it themselves with minimal guidance. Once the user completes the tutorial session of the application, they will be transported back to the Home page, there, the user is able to repeat the tutorial mode should they feel they missed any information. However, the user will also be able to access the transcript of the tutorial so they can easily browse through the steps to quickly study the information.

Once the user is confident, they can access the Assessment mode. Within the Assessment mode, the user is transported to the exact same environment as what was presented in the Tutorial mode. The performance of a person's memory retrieval is enhanced within a surrounding with high visual resemblance to the surrounding at the time at which the memory was encoded. Taking advantage of this also promotes long-term memory retency [15]. Within the scene, the user will be given a list of goals to be completed. From there, the user is then allowed to decide their steps of action by themselves and follow them. However, since one of the core lessons of this training is the safe and correct operation of a lathe machine, any steps that were performed out-of-order shall be recorded, which will be reflected in the result of the assessment. Additionally, the operation of the machine must also be aimed with the resulting workpiece in mind. Therefore, another facet of the result of the assessment shall revolve around whether the final workpiece that was created satisfies the goal given to the user or not. As such, the user is evaluated both in terms of the safety of their actions and whether they are able to achieve the machining of the desired final workpiece or not. It is, however, understood, that the user may have the occasional lapses of memory and adding pressure to the learning process may create an adverse effect on the ultimate goal of training the user, it is therefore proposed that the user will have a choice of restarting the Assessment process as many times as they need until they are satisfied with their performance. While this may seem to go against the assessment aspect of the application, it should be emphasized that the ultimate goal of this research is to create an application which promotes an enhanced learning experience and accessibility of machining operation training. As such, the application should accommodate for the different learning rate of each individual and instead focus on allowing the user to learn at their own pace, repeat the tasks as they desire to do. Doing so will ensure that everyone who has experienced this application will be equipped with the basic operational procedure of a machining process using a lathe machine, which is a skill that is vastly useful in the manufacturing industry.

5.5. Integration with Salesforce

To allow users to submit their assessment results to be recorded, the application must be integrated with a database platform. The platform should allow for the storage and review of assessment results, resulting scores, and the time it took for the user to complete the assessment. Furthermore, to allow the supervisor or related person to monitor the progress of completion of the users, there should be an automated notification system to alert the related parties about the completion and the result of the assessment. To achieve this, the VR integration interface developed by Tangjitsitcharoen and Lawankowit [16] is leveraged; including the Salesforce integration of data management, authorization flow, system architecture, and the record trigger flow.

The data structure constructed allows for the easy maintenance of list of users, stored in the form of Account records. This object is designed to represent unique users who are authorized to access the VR application. Utilizing the Salesforce's standard object, Account object augmented with custom fields, the administrator is able to import a list of users, along with configuring the appropriate password for each users to log-in, their unique identification number, and their designation. All of this information is stored as part of the Account records. This process is illustrated in Fig. 16.

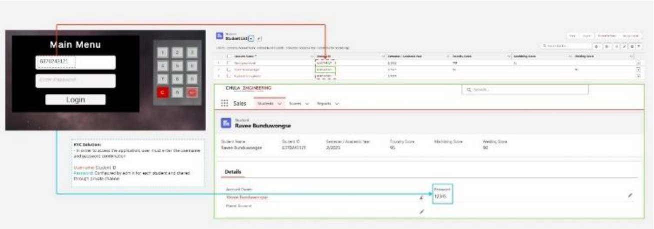
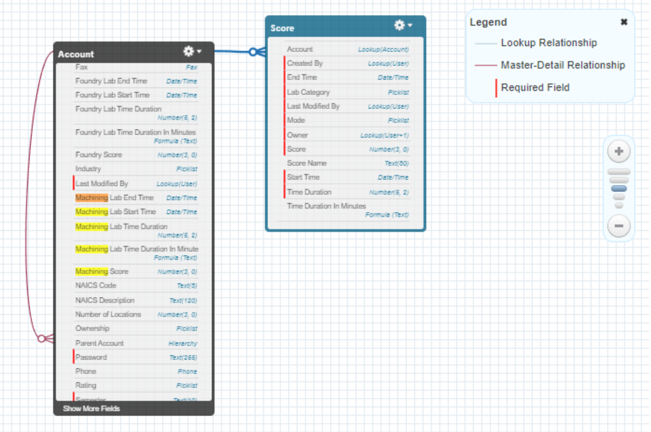


Fig. 16. User verification process using Salesforce.

Once the user completes an assessment mode, the application, connected with Salesforce via Salesforce's Connected Apps and authenticated using OAuth 2.0 client credentials to ensure adequate only the authorized application is allowed to make record updates [16]. As a new score is submitted to the Salesforce platform, a new record under the custom object Score__c will be created. This record of the user's assessment result will have a lookup relationship to the user's Account record, as shown in Fig. 17, associating the score to the user. The study utilizes the Salesforce's Schema Builder to visualize and map the relationship between the objects [17].

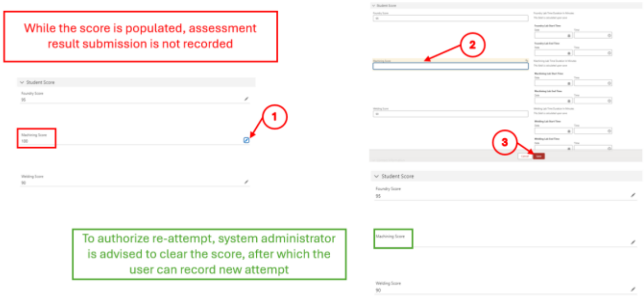


Account	
Fax	Fax
Foundry Lab End Time	Date/Time
Foundry Lab Start Time	Date/Time
Foundry Lab Time Duration	Number(5, 2)
Foundry Lab Time Duration In Minutes	Formula (Text)
Foundry Score	Number(3, 0)
Industry	Picklist
Last Modified By	Lookup(User)
Machining Lab End Time	Date/Time
Machining Lab Start Time	Date/Time
Machining Lab Time Duration	Number(5, 2)
Machining Lab Time Duration In Minute	Formula (Text)
Machining Score	Number(3, 0)
NAICS Code	Text(8)
NAICS Description	Text(120)
Number of Locations	Number(3, 0)
Ownership	Picklist
Parent Account	Hierarchy
Password	Text(255)
Phone	Phone
Rating	Picklist

Score	
Account	Lookup(Account)
Created By	Lookup(User)
End Time	Date/Time
Lab Category	Picklist
Last Modified By	Lookup(User)
Mode	Picklist
Owner	Lookup(User+1)
Score	Number(3, 0)
Score Name	Text(80)
Start Time	Date/Time
Time Duration	Number(5, 2)
Time Duration In Minutes	Formula (Text)

Fig. 17. Salesforce Object Schema layout.

This data association allows for each user to submit more than one assessment result. To disallow unauthorized assessment re-attempt, the developer has included a validation logic to ensure that when a Score submission is made, the system must validate whether the Machining Score field under Account record is empty before proceeding. If the Score record is created successfully, the Account's score field will update, signifying that the user has completed the assessment. The administrator is able to clear the associated exam score under the target Account record to authorize users to re-attempt the assessment as shown in Fig. 18.



While the score is populated, assessment result submission is not recorded

To authorize re-attempt, system administrator is advised to clear the score, after which the user can record new attempt

Fig. 18. Recommended score maintenance procedure.

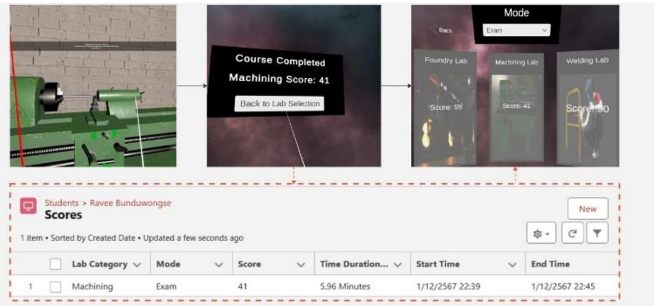
Lastly, the record-triggered flow, allowing for an automatic e-mail notification to the related people is also leveraged. Once the score is updated for a user, the record-triggered flow is triggered, and the appropriate information is sent via Salesforce's email service [16, 18].

As such, to integrate to the groundwork laid by Tangjitsitcharoen and Lawankowit [16], the application must utilize SalesforceAPIUpdateScore.InsertScore method and implement input the parameter and the appropriate logic for the labCategory, score, mode, callback as detailed in Table 14.

Table 14. Salesforce integration method input logic.

Parameter	**Data type**	**Source**
labCategory	String	"Machining"
score	String	Scoring matrix, converted to string
mode	String	Picklist of either "Training" or "Exam"
Callback	System.Action<bool>	Trigger system action to navigate to the score summary screen if completed

This implementation integrates to Salesforce platform via OAuth 2.0 API, which is an API designed to allow external applications to access Salesforce resources securely [16, 19]. In this particular application, the application must first request for the accessToken for score update, to accomplish this UnityWebRequest is implemented [20].



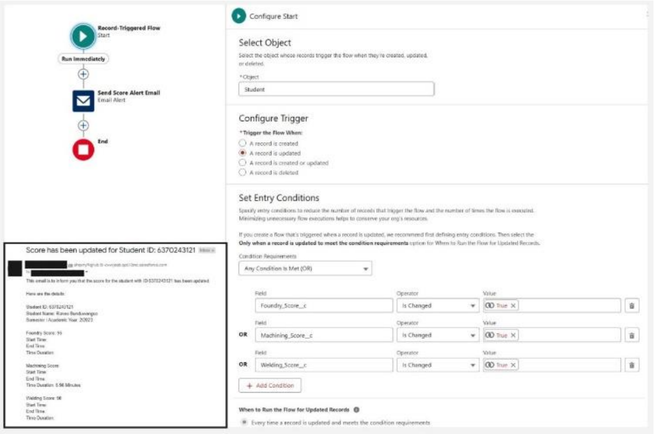
Course Completed
Machining Score: 41
Back to Lab Selection

Students > Ravee Bunduwongse
Scores
New
1 item • Sorted by Created Date • Updated a few seconds ago

	Lab Category	Mode	Score	Time Duration...	Start Time	End Time
1	Machining	Exam	41	5.96 Minutes	1/12/2567 22:39	1/12/2567 22:45

Fig. 19. Assessment mode completion, results in "Score" record creation, which is then recorded and displayed on the "Exam mode" screen.

In addition to the score being recorded on Salesforce database and fetched by the Unity application for display when browsing the Exam Mode in the main menu, the implemented Email notification logic by Tangjitsitcharoen and Lawankowit [16] is also integrated with the Machining Lab. The configuration is shown in Fig. 20.



Score has been updated for Student ID: 6370243121

[redacted]

Configure Start

Select Object

Select the object whose records trigger the flow when they're created, updated, or deleted.

*Object: Student

Configure Trigger

*Trigger the Flow When:
○ A record is created
● A record is updated
○ A record is created or updated
○ A record is deleted

Set Entry Conditions

Specify entry conditions to reduce the number of records that trigger the flow and the number of times the flow is executed. Minimizing unnecessary flow executions helps to conserve your org's resources.

If you create a flow that's triggered when a record is updated, we recommend first defining entry conditions. Then select the **Only when a record is updated to meet the condition requirements** option for When to Run the Flow for Updated Records.

Condition Requirements: Any Condition Is Met (OR)

	Field	Operator	Value
	Foundry_Score__c	Is Changed	True
OR	Machining_Score__c	Is Changed	True
OR	Welding_Score__c	Is Changed	True

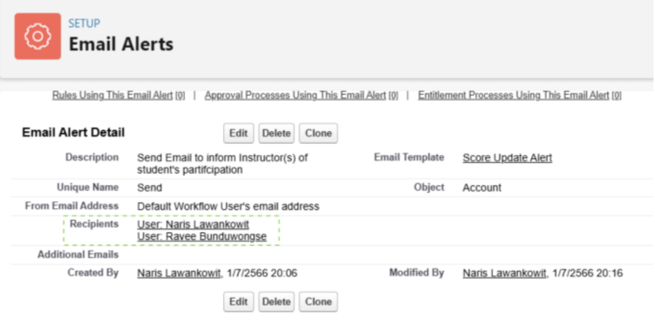
+ Add Condition

When to Run the Flow for Updated Records

● Every time a record is updated and meets the condition requirements

Fig. 20. Email notification Record-Triggered flow [16].

When a score record is submitted, the score breakdown of the student record is then sent to the configured e-mail recipient, to configure the recipient, the administrator can do so by following the screenshot shown in Fig. 21. This menu is accessible via Setup under the Email Alerts settings.



SETUP
Email Alerts

Rules Using This Email Alert [0] | Approval Processes Using This Email Alert [0] | Entitlement Processes Using This Email Alert [0]

Email Alert Detail Edit Delete Clone

Description	Send Email to inform Instructor(s) of student's partifcipation	Email Template	Score Update Alert
Unique Name	Send	Object	Account
From Email Address	Default Workflow User's email address		
Recipients	User: Naris Lawankowit User: Ravee Bunduwongse		
Additional Emails			
Created By	Naris Lawankowit, 1/7/2566 20:06	Modified By	Naris Lawankowit, 1/7/2566 20:16

Edit Delete Clone

Fig. 21. Email Alerts configuration for managing recipient list.

6. Result and Discussion

6.1. Application Result

As the result of the development, a VR application with content focused on the operation of a lathe machine to conduct machining operations is created. The scene includes the following 3D assets, the lathe machine and its interactable components, the workpiece, threading die and cast tool, and a drill press, as shown in Fig. 22. These assets are the main method by which the user will conduct the machining operations exercises.

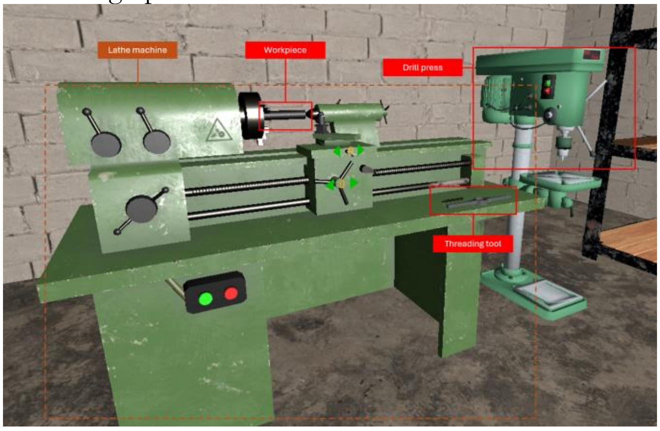


Fig. 22. 3D assets included in the scene.

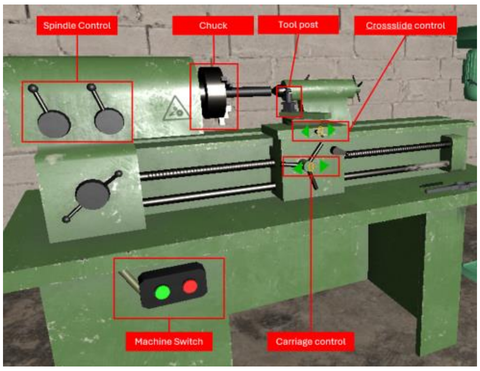


Fig. 23. Interactable components of the lathe machine.

Breaking down the interactable components of the lathe machine, the interactable components include the machine switch, spindle control, chuck, carriage and cross slide control, chuck, and the tool post as shown in Fig. 23. Firstly, the machine switch operates using the Unity physics engine, implemented by applying the Rigidbody and Box Collider components, allowing for the user to directly interact with them in order to turn the machine on and off. Next, the spindle control, chuck and the tool post are operated using the Unity engine's XR Simple Interactable and Box Collider components, allowing for the user to interact with them via a point-and-click style interaction. Lastly, the cross slide control and the carriage control are implemented using a parent UI canvas object with Graphic Raycaster component allowing for the children button objects to utilize the standard Button functionality interactable via a point-and-click style interaction.

The workpiece cutting simulation logic combined with the pre-made models and particle effects resulted in a satisfactory representation of the machining laboratory. As shown in Fig. 24, operations which can not be simulated using the Box collision cutting method are represented using pre-made models to reflect the cutting results, chamfering operation and threading operations are shown.

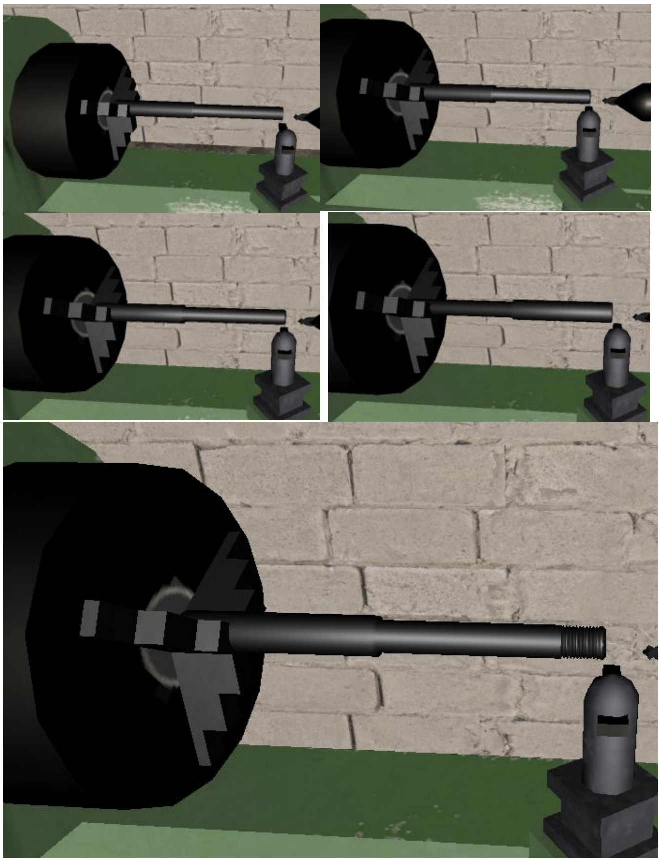


Fig. 24. Pre-made models used to simulate chamfering operation and threading operation.

One restriction posed by using such method is that operations that are simulated using the Box collision cutting method must all be conducted before the operations requiring pre-made models, since it would not be possible to utilize the Box collision method, which requires dynamic generation of the discs, which would not be possible after Pre-made models, which contain complex geometry not replicable with simple shapes. To rectify this, with more computational capabilities, it might be possible to instead represent the workpiece slices in other configurations. Referring to Fig. 25, Option A, which substitutes cylindrical slices with circular sectors, would open the possibility of eccentric cutting operations such as threading, and central cutting operations, such as drilling or boring. Meanwhile, Option B, which involves representing the slices in finer resolution, with smaller increment of cylinder diameter between each slice, would open the possibility of chamfering operation.

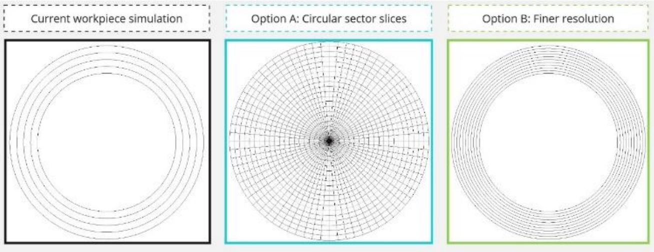


Fig. 25. Possible improvement of workpiece simulation configuration.

Fig. 26. Lathe operation in actual lab.

The particle effect component used to simulate the generation of chips from cutting the workpiece is compared by Fig. 26 and Fig. 27.

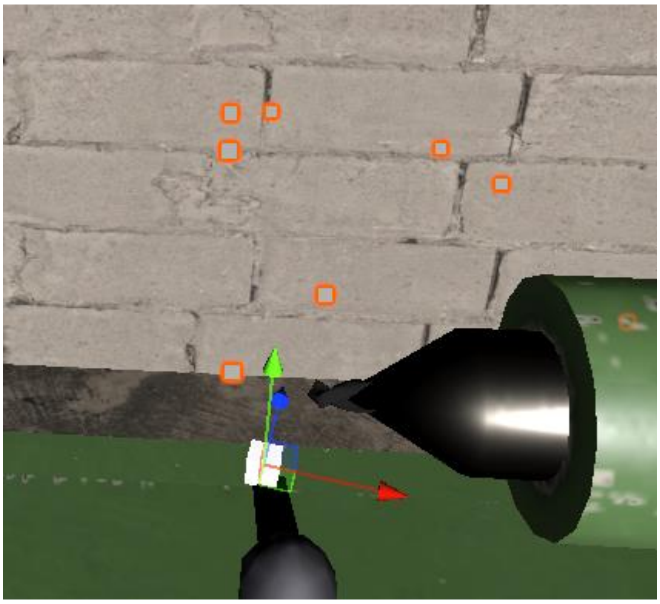


Fig. 27. Highlighting the particle effect representing cutting chips.

The clamping chuck, which secures the workpiece to the spindle is operated and can tighten and loosen. The standard Transform operation is applied and a Coroutine is used to display the animation of the chuck tightening and loosening, as shown in Fig. 28.

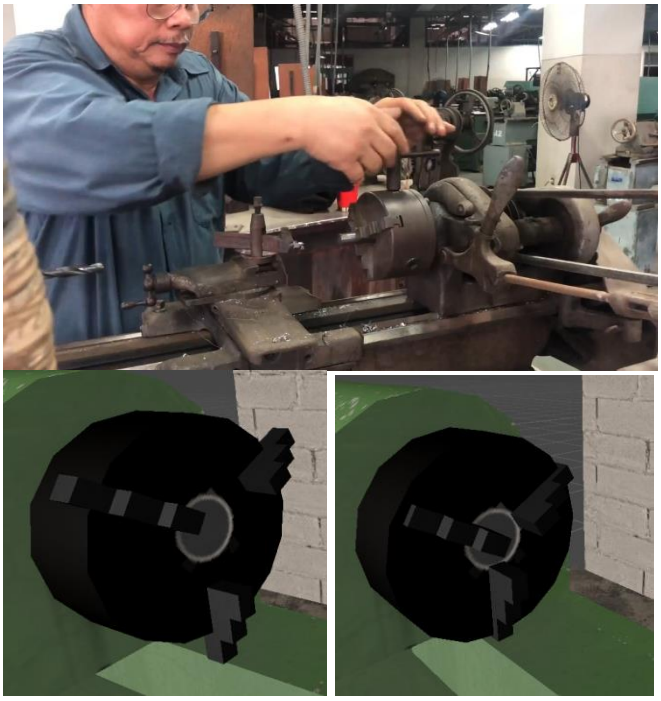


Fig. 28. Adjustment of chuck jaws operation.

6.2. Analysis of Application and Real-World Processes

While there are procedural differences a user may follow based on the cutting plan, the VR simulation is able to simulate the real-world class of machining operations. With the hardware limitation of current VR headsets, subtle user interaction, such as the operation of handwheels of the carriage, cross slide, or the tailstock is not possible. Therefore the less optimal interaction via point-and-click is implemented instead. Although, animation of the lathe machine would still be able to familiarize the user with the various movements of the machine, future improvements can be made when VR hand tracking is able to capture small hand movements and gestures. Large movements, such as pushing of the power button, meanwhile, is able to be simulated and therefore implemented accurately.

Fig. 29. Demonstration of a user using the VR device.

Another main difference is the lack of freedom in the order of operation, due to the limitation of the Box Collider cutting method, the steps by which the operation can be performed must be fixed, starting from facing the ends, then turning, after which the pre-made models are then used to simulate the operations.

In regard to the number of operations conducted in accordance to the machining laboratory compared to the content represented within the VR application, the result can be referred to as shown in Table 15. The facing operation is conducted in accordance with the machining laboratory teaching material, as is turning and grooving operations. The chamfering operation, while simulated using the pre-fabricated models, are still aligned with the machining laboratory teaching material, in which the lathe machine operation is correctly conveyed. The threading operation on the hammer head workpiece is conducted on the drill press, as is aligned with the material. However, the threading of the hammer handle, as discussed previously in Chapter 3.3, is performed with a threading die, instead threading using a lathe machine, which differs from the machining lab.

Table 15. Analysis of accuracy rating based on operations representation.

Operation	Weight	Is represented (1: Yes, 0: No)	Weighted Score	Remark
Facing	4	1	4	Fully represented
Turning	1	1	1	Fully represented
Chamfering	9	1	9	Fully represented
Grooving	2	1	2	Fully represented
Internal Threading (Hammer Head)	1	1	1	Fully represented
External Threading (Hammer Handle)	1	0	1	Use threading die instead of lathe machine
Total	18		17	17/18 ≈ 94%

Analyzing the frequency of the operations conducted, the weighted accuracy results in a 94% rating, with only the external threading operation represented differently from the actual processes, with all other processes represented in accordance with the actual process.

With improved computational capability from VR headset hardware improvement expected in the future, the operations may be better represented with a finer representation of the workpiece cutting slices. The enhanced cutting simulation model would open for threading operation to be conducted solely on the lathe machine, which would result in an even better accuracy rating. Differing cutting condition can also be represented, such as differing cutting speed, order of operation, and feeding pattern. Additional contents and user interactions may also be added, such as removing cutting chips, application of cutting fluid, or representation of result of incorrect operation attempt.

7. Conclusion

This study aims to develop a VR application for industrial training about the Machining operation. While the main proponent behind this was the impact of COVID-19 on on-site classes, other benefits have been explored, such as the freedom to repeat the content without location or time limitations.

While there are limitations of the application, from current VR headsets in the market limitation to tracking subtle hand movements, to computational capacity limiting simulations of the cutting phenomenon. This resulted in the reliance of a novel "Pseudo-Mesh update" via collider logic.

The application is able to convey to the user the significance of different cutting tools for different machining operations, the significance of tailstocks, and the addition of threading tool application. Future enhancements are encouraged, as the application logic is designed with modularity in mind and as computer vision technology improves, the motion tracking capability of VR headsets should improve, allowing for a more realistic operation of the machine, such as the feeding mechanism of a lathe machine using handwheel operation. Better cutting simulation methods can also offer a more realistic and diverse machining operation to convey, such as drilling or boring operations. Operations which involve chamfering can also be simulated with a finer resolution by which the workpiece slices are represented.

Disregarding future hardware improvements, the content of the application may also be expanded, as the step tracking and validation system allows for more input combination, given enough pre-made models are available for different orders of operations, differing cutting speed, cutting depth, and differing feeding orders.

In conclusion, the application can replicate 5 machining operations and educate the user on the appropriate steps by which these operations should be conducted. In addition to the machining operation content conveyed, the application also implements a score database and notification system which allows for a real-time report of the user's attempt to an exam. This involves an email notification system in which the instructor can receive the details of which the result entails. In terms of likeness to real machining lab training, this application can replicate the operation of both 2 workpieces with a total of 17 operations represented accurately out of 18 operations when compared to real machining lab training. With the only exception being the threading of the hammer handle misrepresented from the actual process, the accuracy rating of the application is at 94% when compared to the actual machining laboratory teaching material. More in-depth demonstrations and user interaction can further be implemented when future VR headsets hardware enable for a more accurate representation of the machining operation.

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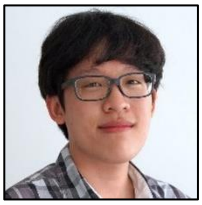

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