An Open-ended System in Virtual Reality for Training Machining Skills

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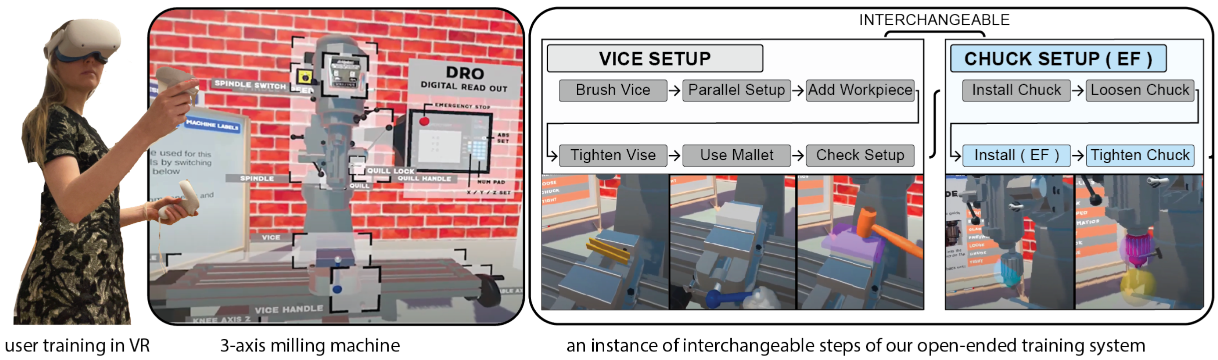

Figure 1: We present an open-ended VR system for training machining skills, particularly for drilling using a 3-axis milling machine. Our system allows multiple pathways to achieve goals wherever feasible while enforcing strict protocols when necessary.

ABSTRACT

With the rise in exploring Virtual Reality (VR) to enhance the training of psychomotor skills, several systems have been designed within the manufacturing sector to train for machining skills. However, existing industry training programs often lack the flexibility to accommodate human error and the adaptability to allow multiple paths to achieving the end task goal. We address this limitation through our VR training system by adopting an open-ended approach to system design. In this interactivity demo, we present our VR training simulation which is specifically tailored for practicing drilling skills using a 3-axis milling machine. This simulation offers an open-ended learning experience, guiding users through safety protocols, setup procedures, drilling tutorials, and open-ended practice sessions. It provides real-time feedback on mistakes and failures and an evaluation of the drilled geometries. For the demo, participants will train for the drilling task with our open-ended VR tool.

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CCS CONCEPTS

• **Human-centered computing** → **Interactive systems and tools**; **Virtual reality**; **User studies**.

KEYWORDS

Psychomotor Skills, Virtual Reality, Open-ended Practice

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1 INTRODUCTION

With conventional classroom and hands-on workshop training approaches for manufacturing skills like welding and drilling [22, 23] being difficult to scale, virtual reality (VR) training environments are explored widely as a scalable alternative [1, 12]. Furthermore, VR offers the opportunity to design adaptable and personalized training to provide efficient and effective training to a wide variety of learners, thus increasing accessibility while saving training costs [4, 15]. Recent studies have demonstrated that VR is effective for training manufacturing tasks like welding and preparing trainees for real-world work environments.

However, much of the design of these existing training systems and tools in VR follows a closed guidance-based tutorial approach. Such a prescriptive method can often limit the trainee's open-ended exploration, user engagement, and error management during their training. Some guided tutorials offer minimal interactivity, essentially reducing user engagement to clicking a "next" button, thus restricting exploration [24]. Others that permit more interaction still confine goal achievement to a single predetermined pathway, limiting trainees' understanding and learning of different tools and approaches [11].

On the other hand, an open-ended approach to designing tutorials involves affording more freedom to explore and learn multiple ways of achieving the same end goal. In our work, we present the prototype of an open-ended VR system for training machining skills, particularly for drilling using a 3-axis milling machine (Figure 1). Our system allows multiple pathways to achieve goals wherever feasible while enforcing strict protocols when necessary. For instance, when setting up a milling machine for an edge-finding operation, users have the flexibility to perform tasks like locking the spindle, turning it on, and adjusting the spindle speed in any order, provided that spindle speed adjustment occurs after the spindle is on. Our open-ended system employs task analysis and dynamically updates learners' goals during training, granting them the freedom to explore diverse methods for task execution and goal adaptation.

Our prior work [18] on studying the effectiveness of our open-ended immersive VR training that adapts to human error during machining tasks on the learners' performance and training experience, showed that the VR training group successfully completed the machining task of drilling at a higher rate, with fewer mistakes, and in lesser time compared to the control group.

The interactivity session will be the live demo of our open-ended VR training system, guiding users through safety protocols, setup procedures, drilling tutorials, and open-ended practice sessions. The users will get real-time feedback on mistakes and failures, alongside an evaluation function to compare their drilled hole geometries and placements with the ideal task. Through this demonstration, we will be able to present our framework implemented in a full pipeline of a system for training for machining tasks. Our system can be adapted to train for various other machining and workshop-related training courses across various institutions.

2 RELATED WORK

Our work is situated within the HCI research, specifically focused on open-ended frameworks for designing learning systems and the design of XR tools for learning psychomotor skills for applications in manufacturing.

2.1 Open-ended Frameworks for Learning Systems

In learning science, the concept of open-ended learning (OEL) and learning environments (OELEs) play a pivotal role in fostering a learner-driven approach, allowing individuals to determine what and how they learn [10]. Unlike direct instruction (DI), which focuses on prescribed learning strategies and goals, OEL is rooted in constructivist principles and emphasizes that comprehension is mediated by the learner's active involvement and exploration [8, 9]. OEL offers advantages such as flexibility [26], personalized and student-centered approaches [19], and fostering self-directed learning [16], thereby enriching the learning experience.

In the area of learning psychomotor skills, studies have explored the impact of different learning strategies [20, 21], such as constant practice (CP) versus variable practice (VP) on skill acquisition. While earlier studies have favored VP over CP [17], recent evidence by Ianovici and Weissblueth [14] suggests that CP is more beneficial for novices, whereas VP is advantageous for experienced learners. However, unlike the focused nature of motor skill studies, manufacturing professions demand a diverse skill set, encompassing both fine and gross motor skills [1]. Workers must discern goals and situations to effectively employ various skills to complete tasks. For instance, machinists are tasked with setting up, operating, and disassembling machine tools, aligning and adjusting cutting tools and workpieces, and employing different tools and machining specifications to shape machine workpieces within specific parameters [27]. It's crucial to note that a machinist might never replicate the same part. Despite this complexity, there's limited research that integrates insights from open-ended learning theories into manufacturing skills training.

Our work addresses this gap by exploring the design of an open-ended training system in VR for machining skills like drilling.

2.2 XR Tools for Learning

Extended Reality (XR) systems have proven effective in fostering skill acquisition across diverse domains, encompassing medical, safety, engineering, and industrial sectors [1, 12, 15]. XR technology has demonstrated its efficacy in enhancing both gross and fine motor skills acquisition, evident in assembly tasks, surgical procedures, welding techniques, powered wheelchair maneuvering, and laboratory practices [2]. Virtual Reality (VR), in particular, holds significant promise in psychomotor skills training due to its interactive nature, embodiment features, consistency, replicability, and safety benefits [1]. For example, intelligent tutoring systems (ITS) establish learning objectives (for example, shooting a ball at a basket) while allowing multiple ways for users to enhance their performance, such as multimodal feedback, actuation for correcting motor tasks, and adjusting task difficulty levels [28, 29]. These systems also provide real-time instructions or recommendations for users' adjustments [6].

Researchers have recently begun exploring the use of this approach for learning psychomotor skills for applications in manufacturing skills like assembly and welding in XR [4]. Through multimodal interactions, sensory engagement, and analytics like training assessments, performance evaluations, and playback features, XR systems offer instructor assistance for varied industrial tasks [7] and target populations [3] However, most of the existing work has primarily focused on cognitive skill development [5, 13, 25]. To the best of our knowledge, limited research has specifically categorized virtual environments based on their open-ended characteristics or explored their impact on psychomotor skills particularly for manufacturing applications.

In our work, we present a prototype of an open-ended VR system for training manufacturing and machining skills, particularly for drilling.

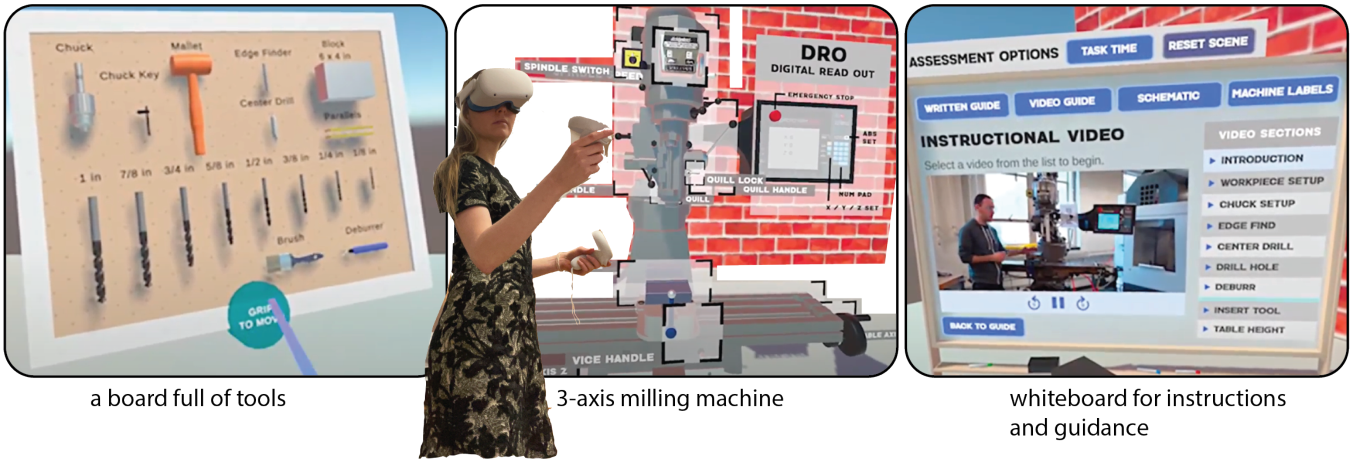

Figure 2: The VR simulation has three components a) a board full of tools b) a 3-axis manual milling machine, and c) a whiteboard of instructions and guidance. With these components, our system guides the users through the training steps for drilling.

3 DEMONSTRATION OF THE SYSTEM

3.1 The Training Tutorial

The VR system has three components, a board full of tools, a 3-axis manual milling machine, and a whiteboard of instructions and guidance (Figure 2). With these components, our system guides the users through the training steps for drilling. The training simulation comprised four distinct modules, each catering to specific learning objectives. The sequence includes familiarizing users with VR interactions, understanding safety protocols, engaging in interactive drilling tutorials, and practicing in an open-ended environment (Figure 3).

3.1.1 VR Tutorial: This initial segment acquaints users with VR controller operations within the simulation. Users learn fundamental actions like object manipulation, such as grabbing or releasing items, and interacting with buttons. This brief tutorial, spanning a few minutes, equips users with essential VR proficiency necessary for subsequent modules.

3.1.2 Lab Safety Module: Focused on safety practices within the machining environment, this module immerses users in a space centered around a whiteboard. Users engage with the two-dimensional surface of the whiteboard, further integrating them into the virtual realm. Within a few minutes, users address crucial safety aspects typically overlooked in VR machining simulations. Tasks involve preparing their avatar displayed on the whiteboard for the laboratory environment by identifying and rectifying potential hazards, like removing jewelry and donning safety goggles. Once the avatar is suitably prepared, users progress to the next module, symbolizing their safe entry into the machine shop.

3.1.3 Drilling Module with Embedded Instructions: This module unfolds within a space housing a whiteboard, a milling machine, and a tool board, guiding users through drilling operations into a 4"x6"x2" metal block. Users access concise video tutorials by a machining instructor and follow step-by-step instructions that adapt to their progress. Rather than imposing restrictions, the guide steers users along correct pathways to achieve the drilling task successfully.

3.1.4 Open-ended Practice in Drilling Module: This segment allows users to apply their acquired knowledge in an open-ended practice setting. Users can self-evaluate their skills using various tools, including a schematic illustrating the position of each drilled hole. In the next subsection, we discuss the open-ended design aspect of our system.

3.2 Simulation Open-endedness

Training systems can be closed-ended when they i) prevent a user from interacting with objects not directly associated with a prescribed task, or ii) do not advance instruction until a prescribed task is completed – even when in reality multiple task orders can complete the goal equally well.

Our system allowed for multiple pathways to achieve the goal of drilling wherever possible (Figure 1). For example, when setting up a milling machine for an edge-finding operation, a user can lock the spindle, turn the spindle on, and adjust the spindle speed, in any order, provided the spindle speed is adjusted after the spindle is on. However, when there is only one order to operate a set of tasks correctly, the simulation requires this one order for users to succeed. For instance, when the drill bit has been installed into the chuck, the succeeding action of drilling a hole has only one correct task order. The user must turn on the spindle, adjust the spindle speed, operate the quill handle to drill the hole, and then turn off the spindle. Finally, the simulation does not gate tasks within one skill from another when the real-life task would not require it. For example, a user in the simulation can also succeed if they set up the chuck and vise simultaneously instead of only one after another.

4 SYSTEM IMPLEMENTATION AND SETUP

We developed an end-to-end open-ended training system implemented for the Meta Quest 2 VR standalone head-mounted display

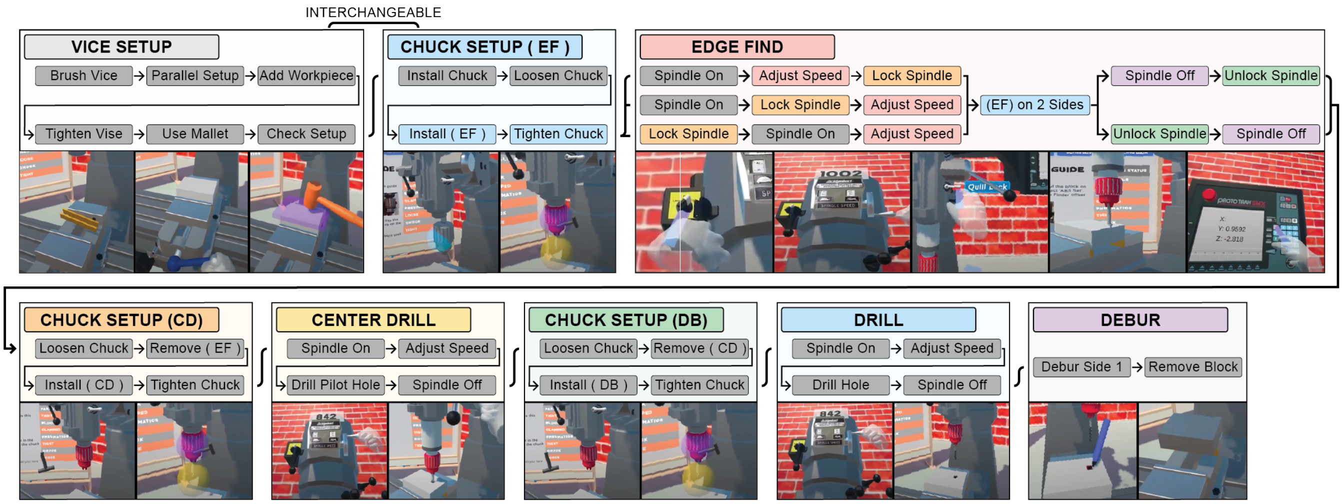

Figure 3: Our open-ended VR system allows for multiple pathways to achieve the goal wherever possible and restricts the users to a single pathway wherever the tool requires a strict protocol for operation. Arrows indicate pathways through tasks, brackets indicate multiple pathways through tasks within one skill, with interchangeability between the tasks in vice set up and chuck set up. (Figure adapted from our prior work [18])

(HMD), employing two Quest 2 controllers within the Unity3D game development environment (version 2020.3.13f). Utilizing the Oculus XR Plugin facilitated the deployment of the APK from Unity for the Quest headset. Integration of inputs and object interactions was achieved through the XR Interaction Toolkit 2.0.3, and our code will be made openly accessible.

Our system offers users the ability to interact with various tools, workpieces, machine components, buttons, and switches at their discretion. It employs warning notifications to alert users of performance errors, such as drilling too deeply or using incorrect spindle speeds. Additional features include the whiteboard, instructional tabs, video modules, and warning/error displays. The tool board presents a familiar layout with labeled tools for reduced cognitive load, featuring snappable and removable tools for task completion and precise tool placement.

During open-ended practice sessions, users are allowed to perform actions within multiple permissible pathways established by task mapping (see Figure 1). The system continually monitors the machine setup's current state and necessary prerequisite tasks for every attempted action. Deviations from permissible pathways prompt error messages on the whiteboard. If an attempted task poses risks to individuals or tools in a physical context, the machine halts, allowing users to acknowledge the error message before proceeding.

In the drilling module, embedded instructions facilitate open interactions akin to open-ended practice. However, the system regulates each instructional step to guide users in completing drilling tasks in a specific correct sequence. Controller interactions predominantly utilize two buttons: grip and trigger. The grip button facilitates grasping and holding various elements, including tools, workpieces, machine components, and area teleportation. The trigger button aids in pressing machine or whiteboard buttons or switches. These interactions support extended reach, employing a line pointer if a machine button is beyond physical reach.

The milling machine simulation, modeled after a Bridgeport EZ-TRAK DX 3-axis manual mill [39], incorporates machine components and interactions layered with visual cues for enhanced guidance. Notable active components include knee, column, 2-axis table, quill, spindle, vise, and digital readout. Instructional guidance is provided via video introductions, step-by-step instructions, diagrams, a guide, and supplementary elements integrated into the user interface. Feedback mechanisms primarily rely on warning and error messages displayed on the whiteboard. Additionally, unique developments, such as a "heat generation" simulator for drilling, and audio cues derived from real machining sounds, aid in sensory-based learning of concepts. These developments offer a novel approach to replicating and enhancing real-world machine shop experiences within the VR simulation environment.

The primary mode of feedback during the activity was through warning and error messages displayed on the whiteboard. Additionally, we implemented features aimed at facilitating the understanding of concepts reliant on sensory feedback, mirroring the expertise of professionals in the field. To aid users in grasping the technique of proper pecking during drilling, we introduced a "heat generation" simulator. As the tool engages with the workpiece, it computes the heat that would be generated in the real setup in relation to its speed, feed rate, and diameter. Upon retracting the drill (pecking) to clear the work, the system decreases the tool's stored "heat" value. Correct pecking practices ensure that the heat value remains below a predetermined threshold. If this threshold is exceeded, an error sign prompts students, indicating improper pecking technique.

Finally, the simulation dynamically alters the cutting sound based on the tool's feed and speed during active cutting. These sounds were captured from the actual drilling sounds in our machine shop. When the mill operates within optimal parameters, a subdued recording is played. Conversely, if the tool is aggressively maneuvered or the spindle speed increases, a higher frequency sound, respectively, indicates discrepancies in operation.

5 CONCLUSION

In this work, we present an open-ended system for VR-based training of machining skills like drilling using a 3-axis milling machine. The system offers an end-to-end training pipeline that allows the users to explore multiple ways of training for machining tasks. We believe that our system presents the prototype for several exciting potential opportunities to design open-ended systems in Virtual Reality for training manufacturing and other psychomotor skills.

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