Immersive Virtual Reality Error Management Training for CNC Machining Setup Procedures

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Immersive Virtual Reality Error Management Training for CNC Machining Setup Procedures

by

Matthew Ryan

Thesis submitted in partial fulfillment of the requirements for the degree of

Master of Science
in Industrial and Systems Engineering

Kate Gleason College of Engineering
Rochester Institute of Technology

22 April 2022

Submitted To the Committee Of:
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Immersive Virtual Reality Error Management Training for CNC Machining Setup Procedures

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Matt Ryan

Submitted to the
Kate Gleason College of Engineering
Department of Industrial and Systems Engineering
in partial fulfillment of the requirements for the
Master of Science Degree
at the Rochester Institute of Technology

Abstract

In order to address the expanding manufacturing talent gap for skilled machinists and limitations with existing machining training programs, this study introduces an immersive Virtual Reality (VR) computer numerical control (CNC) machining training environment CNC machine setup processes with a novel error management-based training curriculum. Current machinist training programs typically require active mentorship from skilled individuals over several years and consume a large amount of materials and tools. In addition, mistakes and errors made during the setup process can create safety risks, waste material, and break equipment, which have not been considered by the existing VR CNC milling training environments. In order to address these operational challenges, a novel error-management based training in VR is proposed, which allows trainees to learn machine setup procedures, common errors and mistakes, and provide an opportunity to practice identifying errors. The training first introduces students to the setup procedure, followed by demonstrations of error cases and identification and management strategies culminating in practice opportunities. Through the VR system, trainees witness a spatial demonstration of the procedure, guided by auditory and text instructions with a realistic error identification practice session. In order to evaluate the impact of the novel error management curriculum and the virtual reality training environment, this study compared the efficacy of three training conditions; video based training, video training with an error management module and VR training with integrated error management training. The results of the study indicate error management training increases the mistake identification and correction and task completion time. Participant feedback indicates that an immersive training increases engagement and reduces distractions during the training phase. Furthermore, participants feel more confident by asking fewer questions in order to operate the CNC milling machine. These findings suggest further developments of error management training for CNC machining training in an immersive VR environment may improve training outcomes and workforce readiness.
Acknowledgments

I would like to extend my sincerest thanks to Dr. Zhang for his endless support throughout my research journey. I have learned so much from Dr. Zhang and my time in the C-DIME lab. Embarking on the thesis journey and joining the C-DIME lab represented a desire to challenge myself to learn outside the boundaries of course work and begin to realize the future of manufacturing. Thank you for allowing me to entertain ideas once outside of my existing skill set and to pursue these explorations under your guidance and support. I have the utmost respect for Dr. Zhang’s passion, work ethic and commitment. I could be certain that if I had a question or needed guidance, regardless of the time or day. I will cherish the late night conversations in the lab discussing the state of technology, automation and their impact to humanity.

I am so grateful for the opportunity to work with and learn from the other members of the C-DIME lab. I would also like to thank Yiwen Wang for all of her collaboration and assistance with my work and for teaching me so much about user studies, human subject research practices and H.C.I at large. Much of this work would not have been possible without the aid of Yiwen and I am deeply indebted to her. I would like to thank Wenhao Yang for being a sounding board as I learned how to turn concepts into implementations. I’d also like to thank Qin Qin Xiao through whom I’ve become enlightened about new domains in education, cognition and more. To all those in and around the lab, I am so grateful for your support and friendship.

I would also like to thank Mike Buffalin, The Construct makerspace director, for permitting the use of the Tormach CNC for the administration of the user study. My many years working as a Lab Manager at The Construct planted the seeds in my mind for which this work has grown from.

Finally, I’d like to thank my parents for their unending support as I navigate my education, the world and beyond. For the world they have bestowed upon me, I am so grateful. No words can express the totality of their impact on my life.
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Chapter 1

Introduction

The skills gap in United States manufacturing continues to grow daily and it is critical that new skilled talent enter the workforce. The manufacturing workforce in the U.S has decreased from 18 million workers to 12.8 million since 1990, nearly a 30% reduction over the past 3 decades [1]. While the entire manufacturing workforce has decreased over the past 3 decades, manufacturing has maintained its contribution to the U.S GDP around approximately 18% over the past 15 years [3] [7].

The continued productivity and economic growth in manufacturing has been supported by digital manufacturing technologies like CNC machines, automated material handling and robotics [8]. The reduction in manufacturing workforce and sustained growth over time has increased the importance of highly skilled and trained workers in manufacturing. Demand for skilled labor in the manufacturing industry continues to grow as a result of natural growth however it is not met due to the lack of available skilled labor [5]. The replenishment of skilled manufacturing workers is below replacement
rate causing a talent gap to accelerate as the previous generations retire [23]. A survey conducted by Deloitte in collaboration with the Manufacturing Institute indicates that over 2.69 million jobs will open as a result of retirements and nearly 2 million jobs will open over the next 8 years due to natural growth. Currently, only 43% of manufacturing jobs are able to fill the role [23]. This gap demonstrates a clear need for significant workforce training that is capable of attracting younger populations.

Nearly 65% of the machinists in the workforce are over 55 years of age [19] and will be retiring from the workforce in the next decade. Machinists have developed skills and tribal knowledge through decades of experience that are difficult to rapidly teach [14]. The retirement of machinists suggests that there is risk to the loss of knowledge that is transferred to apprentices through exposure. Slow knowledge transfer increases strain on the training methods for incoming machinists.

Existing training methods such as apprenticeships and on the job training are challenged to meet the needs of the expanding skills gap in the United States [2]. State sponsored apprenticeship programs are very lengthy requiring up to 4 years of experience and require supervision from an experienced machinist [14]. Community college environments offer an accelerated training process [6] which can be completed in 18-24 months. Each training program has its own trade offs with apprenticeships creating highly trained workers with variable curriculum and industry exposure.

In order to meet demand for machinists amidst the reduction of machinists in the workforce due to natural retirements, the efficacy of training needs to be maximized. The use of technology has become popularized to improve the efficiency of in demand teachers [32]. Video instruction
for basic machining tasks allows instructors to focus their attention and instruction on complicated concepts and tasks [32]. Digital instruction reduces the frequency and repetition of content from instructors, so their time can be utilized where most effective [32]. While the use of technological instructional aids has proven beneficial in applied instances, filmed content faces many limitations when applied to machining instructions [37]. Video instruction faces limitations with complex tasks where simultaneous processes are required [37]. Furthermore, the planar nature of the medium creates an additional cognitive load to interpret the perspective of the environment where cases are not intuitive [24]. With such limitations, researchers have been investigating technological instructional aids such as augmented reality and virtual reality headset devices.

The adoption of spatial computing technologies, the term for all forms of three dimensional virtual and real content (as illustrated in Figure: 1.1), has been accelerated by affordable and quality wearable devices reaching mass production. Virtual reality devices allow for full immersion into a virtualized environment with a dynamic perspective of the environment. In recent years, several companies have released devices capable of displaying high definition content for under $400 [11] [4]. VR devices are no longer cost prohibitive with extensive performance restrictions. Thanks to rapid innovation and mass production, VR has emerged as a capable platform for a variety of applications.

Machining training using VR has shown fundamental advantages over video and traditional training. The primary benefits of initial virtualized machining training include the improved efficiency, safety, cost reduction. Delivering basic content on milling machine operation has allowed instructors to focus on complex training instead of time consuming repetitive delivery. Virtualized environments
do not present the same safety risks because the student is not exposed to any unfamiliar machinery. Students can understand the machines before exposing students to real safety hazards. In a similar nature, VR provides cost savings during the initial phases of familiarization and training. In a VR machining environment, students are not consuming materials and tooling to complete their preliminary training. The improved efficiency, reduced cost, and reduced safety concerns suggest opportunities for continued development and training in a spatial computing modality.

Current explorations of a virtualized machining training present an environment for students to interact with manual and computer numerically controlled machines. The focus of these initial developments has been concentrated around the simulation of the workpiece during the cutting process [42] [28]. Significant opportunities exist in the expansion of scope to cover the wide domain of tasks included when machining. Current works simulate machines operating ideal case environments. Additionally, the instructional efficacy of the systems lacks critical considerations from a cognitive and learning science perspective.

While AR and VR are promising platforms for the spatial instruction of machining, instructional
CHAPTER 1. INTRODUCTION

delivery critically influences the effectiveness of the training and has not been well studied for VR machining. A substantial body of research [29] [26] [22] in the domain of psychology suggests that training for novel tasks like machining are more effective when designed and presented in a dynamic error management approach as opposed to a procedural error avoidance methodology. Error management training “encourages exposure to errors during initial skill acquisition so that learners can be equipped with important error identification, management, and metacognitive skills” [22]. Additionally, the inclusion of errors improves long term knowledge transfer [29]. Error management training is commonly utilized in environments where the cost of making a mistake is very high and the operator requires specialized domain knowledge. Error management is frequently deployed for surgery training [43] and pilot training [27] and while the cost of errors does not have a direct impact on livelihoods, the cost of damaged tools, material, machines, downtime and potential harm, the costs of errors is very high in the machining process. Furthermore, operation of CNC milling machines is technical with specific engineering knowledge required. The combination of high cost of error and technical knowledge parallels existing tasks with error management training and similar benefits may be yielded when applied to machining training.

The first step of the CNC machining process is known as the set up. Errors during setup propagate through the entire process and manifest as dimensional quality defects that may not be detectable until the machining process has concluded. Training material regarding error management or the impact of mistakes is extremely limited and sparse despite the outsized impact that errors during machining setup have throughout the entire machining process. This gap in existing training in a
CHAPTER 1. INTRODUCTION

high impact area is well suited for application of error management training curriculum. It is critical that advancements in training continue to be relevant and prepare students for realistic environments they will encounter in their future work and advancements in machining technology have prioritized familiarity with CNC machines as manual machines become less prevalent. The continued advancement and utilization of automation in machining operations increases the importance of machining setup. Automation has seen notable adoption for machine tending, loading and unloading material and parts automatically however the complexity and variability of setups limit the reasonable completion to be done by a human. As technology evolves, machinists will still be required to set up the milling machine and choose proper fixturing and coordinate systems. Training students for tasks they will continue to perform regardless of technological evolution is important for the robustness of the workforce.

In summary, a large need for machining training exists due to the decreasing workforce size as a result of an aging population preparing for retirement. This need for machinists necessitates robust and efficient training programs however there is a gap between current training programs and industry requirements. New developments in training fail to include instructional methods to assure effective training and meaningful learning outcomes in critical tasks. Therefore, to address this gap, this work proposes the use of virtual reality to deliver machining training that focuses on error management for machining set up tasks.
Chapter 2

Literature Review

This work draws inspiration from existing literature in three primary domains including traditional machining training, machining simulation and virtualization and the education and cognition fields related to error management training theory. The existing relevant literature in the three fields are reviewed in the following sections.

2.1 Machining Training

Current machinist training occurs primarily in apprenticeship programs and community college certification programs [41]. Both paths for training heavily emphasize the importance of practical hands-on experience; however, community college programs [36]. Community college training programs operate in a more traditional academic environment with a balance of classroom theory and
experiential practice. Apprenticeship structure may vary depending on region but many have cur-
criculum and standards that are defined by state vocational training program requirements [2]. In
general, apprenticeships focus skills development through on the job training and experiences with
some traditional instructional delivery while academic programs begin with classroom instruction and
reinforce with hands-on experience. The National Institute for Metalworking Skills has established
a certification program for machinists with defined competencies used by many programs, however
curriculum and training methods are to be determined by the instructor/training organization [12].
The NIMS standards have been adopted in both community college environments for student certi-
fication and recognition while some states have adopted and extended the NIMS standards for their
own apprenticeship requirements [12].

The Office of Vocational and Adult Education (OVAE) explored the connections of individuals’
backgrounds and training with their knowledge of CNC machining work [36]. This work reiterates
the perceived value of experiential on the job training. This investigation emphasized that an in-
dividual’s skill development history is exclusive to the job or traditional class environment. The
majority of respondents were found to have had a blend of class based and job based learnings and
continued education throughout one’s career. The OVAE suggests that the combination is the most
effective way to train and learn [36]. The field of machining is constantly evolving with more sophis-
ticated technologies, such as CNC, robotics and tool innovations and continual learning is required
to maintain a competitive edge in the industry. NIMS recognizes the importance of evolving training
and integrating new technologies and provides several training programs utilizing technology aids to
support continuous education [12]. Current training from NIMS is primarily through video training and simulation tools however other opportunities for technology training aids are actively being explored to improve the effectiveness and overall experience [42] [12].

2.2 Machining in Spatial Computing Domain

2.2.1 Virtual Machining

Spatial computing, inclusive of AR, MR, and VR, paired with virtualization of milling machines has long been studied. The virtualization and simulation milling machines procedures were of great interest in the literature starting in the late 1990’s and continuing through mid 2000’s with works successfully recreating the functionality of CNC’s on a computer [25] [13]. These early works were limited by the technology available at the time and were built to virtualize tools on 2D monitors. The objective of these initial systems was to closely replicate machine functionality to allow users to develop familiarity with a milling machine prior to hands-on experience. Not all early investigations of CNC training simulators pursued realism and work done in collaboration with the French National Association for Vocational Training of Adults integrated haptic feedback and dynamics into the training. Given the technological ceiling based on limited graphics power and its influence on visual acuity, researchers investigated the effect of cutting force in haptics. Students were able to understand the influence of cutting tool dynamics based on the haptic feedback [17]. At the turn of 2010’s, computing power was improving, the prevalence of virtual reality headsets increased the degree of
immersion possible and research largely shifted to exploring machine simulation in truly spatial mediums [16] like VR headsets and augmented reality systems.

2.2.2 VR and AR Systems

The accessibility of virtual reality headsets and augmented reality devices has allowed numerous investigations to flourish and advance the understanding of how the nuances of virtual and mixed reality environments can support the full process of machining.

Virtual Reality Machine Simulation

A significant body of work has been focused on the simulation of machine operation in order to improve operator confidence and reduce mental strain. CNC machine tools are programmed to follow a generated toolpath to achieve a final geometry. Current complex toolpath generation processes utilize computed aided machining software [34]. New operators express concern and are challenged to visualize such toolpaths [47] and an application for the familiarization of such toolpaths is proposed by Cukovic. The implementation fully visualizes prismatic tool paths in an augmented reality medium. The system renders the machine, workpiece, and tool. Cukovic claims additional familiarity and comprehension can be achieved in a very low risk environment [47]. Students or new machinists can develop a familiarity with how the toolpaths operate before transitioning to operating real milling machines [47]. This transition from a fully simulated machine to a real machine is the focus of further research of in-situ machine simulation.
CHAPTER 2. LITERATURE REVIEW

In-situ machine simulation has seen evolving advancements with the availability of reliable augmented reality systems. Early attempts to provide additional machining insight were implemented with the development of a custom display solution using a holographic optical element on the CNC lathe window as a result faced several limitations due to the viewing technology [39]. This system displays process information, upcoming NC codes, visualization of cutting conditions and facilitated error notification to the operator creating a centralized oversight of the operation. Since 2008, improved developments for visualizations have emerged and computer vision abilities have improved to allow for accessible in-situ simulation.

In-situ simulation allows operators to verify that the generated toolpath will not interfere with any fixturing during the operations however it does not provide any value during operation. More recent advancements in networked machine tools allow for continuous simulation and additional networked cyber-physical information [35]. The development of an augmented reality “intelligent window” combines real time control, machining simulation and process monitoring with existing data and novel visualizations. Liu suggests that operators can quickly identify a process variation using the tool and material mesh overlays because any variations in the visualization indicate some variations in machine operation [35]. This is achieved through Virtual renders that are aligned in combination with machine data position. Liu suggests virtual controller capabilities are sufficient to replace existing machine controller interfaces.

VR Machining Training
CHAPTER 2. LITERATURE REVIEW

The demand for machinists combined with the opportunity to train with fewer resources has established explorations into the use of technology based training to supplement machinist and milling education. Computer based CNC machining in 2004 demonstrated interaction with machine measurements, interface panel and machine controls [45]. This work demonstrated the feasibility of an interactive CNC machining training environment that inspired further developments as display technology advanced. The European Center for the Development of Vocational Training later supported work to develop a system with a more structured virtual learning environment [40]. This work aimed to develop a usable and highly structured virtual training focused on content delivery as opposed to a highly interactive platform. The work in development of a Virtual Training Center was inclusive of educators, students, policy makers and researchers and suggested that virtual machining training is a critical and strategic component of supporting economic development [40].

VR based trainings are limited in their ability to recreate realistic CNC interactions because of highly complex machine interaction panels. The CNC Partner [33] system aimed to bridge this gap and created a semi-immersive virtual training environment with a physical interface very similar to that found on a standard CNC machine. The CNC Partner effectively demonstrated the ability to simulate and recreate the entire machining workflow and CNC functionality ranging from part setup, measurement taking, manual data entry, NC programming, cycle execution and processing [33]. The comprehensive abilities and physical interactions are supported by teaching support tools like syntax verification, sequence suggestions and a grading and evaluation tool [33]. Recent advancements in VR, AR, computational capacity, and sensor technology created substantial opportunities for improvement with respect to
true spatial immersion. Yang proposed a training system for manual milling that combined a head mounted display with hand tracking and RGB depth sensors to provide a natural interface [46]. The training system allows the user to interact with the virtualized objects in a real environment (AR) with their hands. The effectiveness of augmented reality training was evaluated and demonstrated a reduction of failures during operation combined with fewer inquiries during the setup phase, in comparison to video training [46].

Evaluation of immersive machining training has been the focus of recent literature as industry adoption of virtual and augmented reality is popularized. As the workforce ages, capturing knowledge is an important task for the effective training of a younger workforce. Nathanael evaluated the uses of cognitive task analysis approaches (CTA) as a method to capture expertise in order to extract knowledge regarding the tool offsetting procedure to design a virtual reality training program [38]. The virtual reality training system (VRTS) developed using the CTA approach was found to be more effective than traditional training for new student machining when required to complete a real task on a CNC mill [38]. Systematic extraction of knowledge from expert knowledge improved the effectiveness was shown to be a critical factor for knowledge transfer.

Recent work continues to advance the understanding of cognition and learning of machining tasks in VR. Chen evaluated the learning performances of two different approaches to the design of the instructional content [15]. The approaches evaluated are a sequence based approach and a context approach. The sequence based approach teaches the material in chunks of individual sequential
CHAPTER 2. LITERATURE REVIEW

operations and context provides a systems level approach with content including all operation types from the initial phase of instruction. The two approaches were evaluated and compared, and it was found that the context based approach outperformed sequential instruction and use of virtual training improved user experience [15]. Understanding the instructional and pedagogical design of VR content for machining will allow research to improve efficacy when introduced to real world training environments. The trend to integrate known educational research and methodologies into manufacturing continues with this works introduction of Error Management.

2.3 Error Management

Educational practices like Cognitive Task Assessment show promises in improving efficacy of training in simulation environments. Error management is a training philosophy that embraces mistakes and explores how to identify and recover from them, instead of strict avoidance [29]. The error management strategy has been found to improve the transfer of learning in simulation-based training [20]. Error management training has been largely investigated in literature for use cases where mistakes and errors can have detrimental effects such as surgery [30] and pilot training [31]. Fasciotomy surgical trainees receive procedural instruction followed by an assisted session of error recognition and management training where trainees identify and correct the errors present followed by an unassisted session for evaluation. Surgery trainees would undergo additional rounds of practice if sufficient threshold of mastery was not achieved [21]. Error management training has seen significant adoption
in surgical training, analysis of errors during cardiac surgery classified surgeon behavior to better inform training [44]. The collection and classification of actual performance guided the creation of specialized correction pathways. Due to the nature of surgery, error identification and correction have a finite window for action. This study highlights the nuance of applying a generalized error management and suggests that classification of errors is important, prior to the integration into future training [44].

Error management training philosophy has been extended by the Space Flight Training team at NASA [18]. While mechanical reliability was improving and reducing spacecraft incidents, human error was not decreasing and justified investigating methodologies for improvement. The SFT team extended error management training practices employed by commercial aviation Cabin Resource Management training. The Space Flight Resource Management (SFRM) and Cabin Resource Management (CRM) training work to train pilots and astronauts to “deal with errors committed by detecting and correcting them before they have an operational impact”. As a component of CRM and SFRM, error identification methodologies are reviewed and practiced extensively [18]. Practice of error identification is a key component to successful readiness for crews in space and in those operating in surgery environments. The error management training in simulated surgery environments was shown to improve confidence and reduce errors made during the evaluation [21] however, it has not yet been investigated how to apply error management training strategy into the CNC machining instruction. Successful applications of error management training in a variety of fields suggest that
introduction of error management training strategy to machining could reduce the error made during the operation and improve the overall performance of the trainee.
Chapter 3

Implementation and VR System

The Virtual Reality Training Environment has been built in Unity 3D, a game development and XR engine [9]. Unity3D allows for the integration of existing virtual reality hardware using existing packages. The system has been built to utilize an Oculus Rift from Meta. Unity enables virtual assets like CAD models to be programmatically manipulated, generated and interacted with. The training system is controlled by an extensive number of C# scripts.

Trainees utilize an Oculus Rift 2 [4] which presents an immersive 3D environment. The Oculus Rift 2 tracks the position of the trainee using outward facing cameras and internal motion tracking sensors to localize and track the position of the trainee. The system utilizes the two hand controllers that are tightly integrated with the Oculus Rift system.

Virtual assets are presented in the 3D environment to create a realistic training environment. The workshop environment has been acquired through the Unity Asset Store from TIRGames Assets.
as PBR Workshop. The PBR Workshop asset was purchased and is being used with permission from the designer for research distribution.

The VR system trains students on a virtual Tormach 1100M, a common 3-axis mill found in academic and educational environments. The CAD model is publicly available from Tormach for CNC programming simulation purposes. The CAD model (.step) was converted to a compatible file format (.fbx) using Autodesk 3DS Max (made available through Autodesk Education licensing). The CAD models are being used with permission for research and training from Daniel Rogge, Tormach CEO. Additional machine tool components such as vices, end mills and micrometers utilize CAD models that are publicly available from GrabCAD. These models are converted for use in Unity following a similar conversion workflow with Autodesk 3DS Max.

All components and the corresponding stock material, if used for machining instruction, have been modeled using Fusion 360. Once the original part design was completed, a realistic CAM program was created using the Manufacturing functionality of Fusion 360. Using Fusion 360, the toolpaths were generated for the Tormach 1100 and exported to be processed for visualization and integration to the training program. For ease of processing, Fusion 360 is utilized to export a position only toolpath consisting of only X,Y,Z coordinates.

The system implements a virtual CNC milling machine with the capabilities to move around based on input from a virtualized controller or through the simulated CAM process. The axis of the virtual machine can be manually controlled incrementally ranging from .001” to .1”. Each axis can be controlled independently. Additionally, the functionality of establishing an axis origin point has
been integrated into the control, similar to physical CNC mills or digital readout systems. In order to enhance the understanding of an origin work coordinate system, a virtual coordinate system triad is rendered and remains in its relative position when the machine moves.

The control of the system parallels the common VR interaction tool of a “laser pointer” which acts as a spatial cursor. Trainees are able to interact with buttons on the machine interface with the laser pointer. The laser is created by raycasting the forward vector of the controller and rendering a line in combination with logic to check for collisions and controller button clicking.

![Figure 3.1: Laser Pointer Control and Hand Rendering](image)

In addition to raycast lasers for interaction, trainees are able to physically interact with objects such as tools, stock material and fixtures. Objects can be manipulated using the rendered hands which are overlaid in position of the controllers. Users grab objects by depressing the palm button.
on the controller. The interaction logic for manipulating objects is limited to object positioning.

A core component of the training process is the combination of instructional aids including text, animations, visual indicators and audio queues. Procedural instruction is sequenced using an external file database. The sequencing of the menu text, position of machine, animation object and waypoints, g-code rendering and visual indicators are updated as the trainee progresses through the content.

The VR Environment includes several visual indicators and components to visualize non-tangible machining processes as well as guide the users attention to key areas of interest during the training. These spatial design components are categorized into attention guidance and training and interaction support.

### 3.0.1 Attention Guidance

**Focus Region**

Highlights regions where upcoming actions will be occurring. Focusing attention in a fully immersive environment requires visual highlights as shown below in Figure: 3.2
Figure 3.2: VR Focus Region Indicator

**Point of Interest**

Indicates a specific component or location on component that is of importance to the instructional content [10].
Figure 3.3: VR Attention Pointer

**Viewing Zone**

The viewing zone is the ideal viewing location to stand to watch the demonstration process.
3.1 Interaction Support

Several virtual indicators have been implemented during the training to reinforce spatial concepts that can not be visualized in a traditional training.

3.1.1 Tool Path Visualization

CNC Milling Machines operate off of a computer generated code for machines called G-code. G-code is a universal machine language to be interpreted by machine middleware. G-code can be written manually or generated by utilizing computer-aided manufacturing (CAM) software. The system is
CHAPTER 3. IMPLEMENTATION AND VR SYSTEM

capable of processing G-code and spatially rendering a toolpath in the virtual space. A visualization of the toolpath with the corresponding part can be seen below in Figure: 3.5.

![Figure 3.5: VR Toolpath Visualization](image)

3.1.2 Virtual Work Coordinate System

The active work coordinate system is rendered with an origin triad to visualize changes during the Work Coordinate System (W.C.S) setting process. This overlay is intended to reduce instructional confusion very common in traditional training as a result of the required mental spatial transformations.
3.1.3 Tool Path Execution

The virtual CNC milling machine can process G-code and travel through the path as programmed in the Computer Aided Machining (CAM) program by processing G-code and converting it into virtual positions given the adjustment for the Work Coordinate System.

3.2 Machine Interaction Design

The virtual Tormach CNC machine can be controlled using a virtual Human Machine Interface. The HMI is simplified to allow for a machine agnostic training in addition to prioritizing the functions
required to perform the machine set up process. The functions of the virtual HMI are consistent
across all CNC milling machines and include:

### 3.2.1 Positional Readout

The positional readout presents the distance between the origin point of the current tool and the
Work Coordinate System (WCS). The system is initialized with a default W.C.S however the user
is able to modify the origin point and changes will be represented on the readout.

![Virtual Digital Read Out](image)

Figure 3.7: Virtual Digital Read Out

### 3.2.2 Set Axis Zero

The Set Axis Zero button allows the user to modify the current position of the work coordinate
system. The virtual Set Axis Zero function is completed for each axis independently. The Set Axis
Zero function will update the Positional Readout and the virtual WCS triad.
3.2.3 Axis Jogging

Users can manually jog the machine around using the [+ ] & [- ] buttons on the HMI. Each axis is controlled independently and manual motion can only operate one axis at a time, to match parity with existing CNC machine control fundamentals.

![Jogging Buttons](image)

Figure 3.8: Positional Jogging & Axis Zero Buttons

3.2.4 Jogging Increment

The jogging increments function allows the user to change the distance the machine moves during each jog command. This function matches parity with incremental motion on CNC milling machines. The increments range from 0.1” to .001”. Higher granularity of control is required when locating the work coordinate system on a piece of stock and is important to maintain in the virtual environment.
3.2.5 Spindle Power

Spindle power initiates rotational motion of the spindle and any cutting tool that has been inserted and associated with the spindle. The rate of rotation of the spindle is fixed. The rate of rotation is not an essential factor of the setup process and was subsequently simplified to a fixed rotational speed. Spindle power is shown as the green button in Figure 3.10.

3.2.6 Emergency Stop

The emergency stop button is not critical for the education of the set up process however it was included in the HMI design in order to familiarize trainees with the safety equipment and ease the transition from virtual machine to physical machine. The virtual reality environment does not present any physical machine risks.
3.2.7 Tool Info Panel

The tool info provides information about the CAM program Operation tool requirement and the Currently Loaded tool. The tool info panel design presents the user with the information that would traditionally be found in the CAM program or set up sheet and the CNC machines tool library. The tool info panel includes tool length, diameter, tool type and number of flutes. The tool info panel is required for training & evaluating students on proper tool selection.
3.3 Interactive Feedback

Providing trainees the opportunity to practice their skills in a virtual environment with no repercussions is a large benefit to operating in a virtual environment. The primary activities have been developed to support procedural practice with interactive feedback. The focus for interactive feedback breaks down the process of Work Coordinate Origin Selection in smaller practice tasks.

The first practice activity includes identifying the corresponding corner which matches the CAM WCS shown. Users can receive feedback on the validity of their selection in two ways. Users can control the machine to place the active tool in the region of the corner. Visual feedback in the form of colored spheres indicates the accuracy of the origin choice. This practice of moving the tool
is symbolic and not representative of the procedure and that is emphasized in the training. This activity helps introduce the concept of moving the machine around the part and defining an WCS relative to the part. During the activity, the size and color of the region detector will change if the selection is accurate and close to the corner.

![Progression of Visual Corner Feedback](image)

Figure 3.12: Progression of Visual Corner Feedback

In order to reinforce the concepts required for edgefinding, participants are shown a randomly selected WCS and given the position and orientation, the student has to select the faces of the stock material for the edge finding process and feedback is provided.

### 3.3.1 Workflow

The exact workflow for the WCS Selection Practice is outlined below:

- The CAM WCS presents the reference origin for the participant User selects the corresponding correct on the Selector.

- Feedback is provided, user repeats until correct User is prompted to select the face they will
use as the X axis Zero Origin.

- User selects a given face, face is assigned the corresponding color.

- Users is prompted to select the face they will use as the Y axis Zero Origin.

- User selects a given face, face is assigned the corresponding color.

- User is prompted to select the face they will use as the Z axis Zero Origin.

- User selects a given face, face is assigned the corresponding color.

- User submits completed selections Feedback informs user if a face was correctly selected.
Chapter 4

Training Content Design

4.1 Procedural Training Modules

The procedural training module demonstrates the required tasks and sequence of sub tasks required to the trainee in order to complete the CNC machine set up process. The procedural training modules are broken down into the 3 primary tasks required; fixture selection, work coordinate system alignment and tool length Z offsetting. The design of the procedural training module is driven from the modeling phase of observational learning theory methodology. Procedural training aims to teach the actions and steps that a trainee can follow to complete the task.
CHAPTER 4. TRAINING CONTENT DESIGN

4.1.1 Fixture Selection

The fixture selection procedural training introduces a variety of basic fixturing approaches. The content teaches students on the criteria for proper fixture selection given that part to part geometry variation makes a generalized approach limited.

The criteria for selecting a fixture are that it can satisfy Sufficient Clamping Force and does not interfere with the machining process (access & collisions). Fixtures need to apply a force that is greater than the cutting force while stabilizing and reducing vibrations. The fixture needs to be able to hold with enough force that the part does not move when engaged with the cutting tool.

Due to the prevalence of vices in milling machine set ups, the procedural instructions for securing stock material in a vice are reviewed. Instructional text is outlined below:

<table>
<thead>
<tr>
<th>Vice Set Up Process</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 A vice can be used and adjusted for a wide range of stock.</td>
</tr>
<tr>
<td>2 First, clean the vice of any oil or metal chips.</td>
</tr>
<tr>
<td>3 Place square stock in the center of the vice.</td>
</tr>
<tr>
<td>4 If the stock does not clear the top of the vice, remove the stock and place with parallels.</td>
</tr>
<tr>
<td>5 Place the parallels along the jaws of the vice.</td>
</tr>
<tr>
<td>6 Replace stock &amp; crank the vice handle to clamp the material firmly.</td>
</tr>
</tbody>
</table>

4.1.2 WCS Alignment

The Work Coordinate System Alignment procedure establishes a relative reference to the stock material that the machine will drive machining operations off of. The training acknowledges that there are many ways to establish a work coordinate system with a CNC like probing arbitrary features
or edges however the procedural focus utilizes an edge finder. An edge finder is a tool with a tip that indicates when the rotation is axial. Edgefinders are commonly used for low volume machining and are also used to introduce the concept of work origins in machining education environments.

The procedural text content for Work Coordinate System Alignment is as follows:

<table>
<thead>
<tr>
<th><strong>Edge Finder WCS Alignment Process</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>The edge finder is used to precisely indicate off the stock and locate the edges of the stock.</td>
</tr>
<tr>
<td>The probe is the lower, movable portion of the tool. This edgefinder is placed in a tool holder for use.</td>
</tr>
<tr>
<td>Identify the Work Coordinate System that is being used in the Computer Aided Machining (CAM) program.</td>
</tr>
<tr>
<td>The origin used in the CAM program MUST match the coordinate system that we define on the stock material. Match the origin and orientation.</td>
</tr>
<tr>
<td>Place the edge finder into the toolholder</td>
</tr>
<tr>
<td>Place edge finder into machine</td>
</tr>
<tr>
<td>Offset the edge finder probe to rotate off-center</td>
</tr>
<tr>
<td>Turn the spindle on and run between 500-1000 RPM</td>
</tr>
<tr>
<td>Use machine controls to move the stock and approach the side of the stock that is perpendicular to the X axis and at the origin.</td>
</tr>
<tr>
<td>Slowly continue to move the edge finder to the side of the stock. As the probe and stock contact, the edge finder will wobble less.</td>
</tr>
<tr>
<td>Continue very slowly until the edge finder probe pops out. This is the indication that the tool has come in contact with the edge.</td>
</tr>
<tr>
<td>Now the edge has been precisely located.</td>
</tr>
<tr>
<td>Before we establish the X Zero position of the axis, we need the center of the edge finder to be on the edge of the stock.</td>
</tr>
</tbody>
</table>

**Approach 1**

We can accommodate for the thickness of the edge finder to align the center of the tool with the edge of the stock in two ways.

Using the diameter of the edge finder probe, we can raise the machine and precisely move ½ of the Diameter over the part.

**Approach 2**

Establishing a point that is not the zero but instead ¼ of the diameter offset from zero by inputting the value. Set the current position of the tool to the offset from the desired WCS.

The same exact process is repeated to set the Y axis zero position.

Remove the edge finder and proceed with the tool length process.

Figure 4.1: Edge Finder WCS Alignment Process
4.1.3 Tool Setting

The third component of the machining set up is establishing the Z plane, the plane normal to the machine tool. Defining the Z plane requires establishing a face of the stock at a known height from the tool holder mount. Additionally, CNC milling machines require information about length of the cutting tool to the tool holder flange. The initial reference to the stock material is a constant across all tools. The tool length offset is an offset value used to allow CAM programs to assume the bottom of the tool is the point of reference for all program positional data.

![Figure 4.2: Tool Length Offset (Source: CNC Philosophy)](image)

The curriculum approaches the Z offsetting procedure through two methods. One method commonly taught to inexperienced trainees utilizes a piece of paper and iterative tactile feedback to gauge the top of the stock material. The paper touch off method is the most primitive method however its fundamental approach and frequency in novice training justify its instruction. The second method for establishing a reference plane utilizes a touch tool setter, which is a
measurement device with a known distance from the bottom and top face and reads the deviation from the fixed value. The tool setter is introduced to the curriculum to highlight the possibility of an indirect reference plane definition. During the use of the offsetter, students are instructed to define the known offset distance of the device and not a zero value common with direct touch offs. Advanced CNC operations can utilize custom manufactured fixtures that precisely locate the stock. The use of custom fixturing is typically accompanied with a work coordinate system origin that is entirely offset from the stock material. The tool setter serves as an intermediary to this arbitrary offset and is therefore included in the curriculum.

<table>
<thead>
<tr>
<th>Step</th>
<th>Instruction</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Note: The tool setter is a specialized measurement tool and is calibrated to measure the distance from the bottom of the tool setter to the top of the pressure measurement pad.</td>
</tr>
<tr>
<td>2</td>
<td>Select the desired end mill and place it into a toolholder.</td>
</tr>
<tr>
<td>3</td>
<td>Place the toolholder into the spindle of the machine.</td>
</tr>
<tr>
<td>4</td>
<td>Place the tool setter onto the surface of the stock in a steady and flat region.</td>
</tr>
<tr>
<td>5</td>
<td>Carefully, move the tool until it almost touches the center of the pressure pad.</td>
</tr>
<tr>
<td>6</td>
<td>Very slowly continue to depress the tool offsetter until it reads the calibrated height.</td>
</tr>
<tr>
<td>7</td>
<td>Once at the desired measurement reading, we can set the Z position of the machine by entering the tool setter reading as the Z position. This sets the current position as a known distance away from the stock material.</td>
</tr>
<tr>
<td>8</td>
<td>Raise the tool off the tool offsetter and remove from the stock.</td>
</tr>
</tbody>
</table>

Figure 4.3: Tool Length & Z Zero Procedure: Tool Setter Method
4.2 Error Management Module

Error management training is an approach to training that recognizes that due to human nature, mistakes and errors can occur. Instead of focusing on rote memorization and procedural execution, error management works to integrate training content that addresses potential errors by communicating what they are, how they occur and how to identify the errors. Error management is commonly deployed in domains where a high cost of mistake exists, including medical and pilot training. CNC machining does not present the same high cost of life impact, however serious safety concerns and high financial impacts are present. Given the focus of this work is limited to machining setup, the errors discussed only pertain to the setup procedure and are categorized into the three main sub-tasks of setup.

<table>
<thead>
<tr>
<th>Step</th>
<th>Instruction</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Select the desired end mill and place it into a toolholder.</td>
</tr>
<tr>
<td>2</td>
<td>Measure the distance from the base of the tool holder to the tip of the endmill.</td>
</tr>
<tr>
<td>3</td>
<td>This value is registered as the tool length. Enter into tool library value.</td>
</tr>
<tr>
<td>4</td>
<td>Place the tool holder into the spindle of the machine.</td>
</tr>
<tr>
<td>5</td>
<td>Place a piece of flat paper onto the center of the stock.</td>
</tr>
<tr>
<td>6</td>
<td>Lower the tool slowly onto the paper. Very slightly move the paper back and forth constantly.</td>
</tr>
<tr>
<td>7</td>
<td>Carefully, (small increments) continue lowering the tool until you are not able to move the paper. The tool will snag on the paper.</td>
</tr>
<tr>
<td>8</td>
<td>Move the tool upwards in very small increments of .001&quot;. Once the paper begins to free, stop.</td>
</tr>
<tr>
<td>9</td>
<td>Set the Z position to be the thickness of the paper above Z zero. Paper is typically .005&quot; thick.</td>
</tr>
</tbody>
</table>

Figure 4.4: Tool Length & Z Zero Procedure: Paper Touch-Off Method
CHAPTER 4. TRAINING CONTENT DESIGN

4.2.1 Errors

Common errors that occur during CNC machining setup can be categorized under the sub-task of setup. Through discussion with expert machinists, instructors, and online community feedback regarding the most prevalent mistakes and errors made by novices, 2-3 errors have been selected for each process based on their impact to the overall success of the milling operation. During the training, visuals and animations are presented to demonstrate what the error looks like. The visualizations are medium dependent and vary between the video training and VR. Samples of the visualizations found in the video training and VR training are featured with the description in the following section.

Fixture Errors

Fixturing errors are directly related to mistakes made that impact how the stock material is held to the machine. Fixtures can take shape in a large variety of forms and there is an incredible degree of variation between different workholding approaches. The variability of fixtures used in machining set up introduces a wide set of unique errors that a machinist could make. The errors selected for the training aim to apply generally to all/most forms of workholding. However, many of the examples of errors are demonstrated using a traditional vise due to its prevalence. The three fixturing errors integrated into the training curriculum are as follows:
CHAPTER 4. TRAINING CONTENT DESIGN

**Fixture & Tool Path Collision**  This error occurs when the fixture is located in the same space as a planned toolpath.

*Impact:* The tool will crash into the fixture and will likely break. Damage to the fixture is likely. Depending on the cutting condition and severity of the collision, damage to the machine is possible. Spindles are susceptible to damage if the collision is fast and into substantial material.

*Identification:* Testing of the tool path while not engaging with material will indicate if a collision will occur. To check collisions, run the toolpath above & to the side of the stock material. For complex fixtures, the fixture should be modeled into the CAM process. Simulate the toolpath.

*Mitigation:* Raise the stock material away from the fixture or relocate clamping features.

*Common Cause:* Collisions are commonly the result of not considering how the tool enters and exits the boundary of the stock material.

---

Figure 4.5: Video Illustration of Fixture & Tool Collision
Figure 4.5 illustrates contact between the tool and the vice. The blue toolpaths travel the boundary of the part where the stock is held.

**Insufficient Clamping** Insufficient clamping errors occur when the cutting force from the milling machine is greater than what the workholding is applying to the material. The clamping forces cannot constrain the stock material.

*Impact:* The part will move around and the mill will cut in the wrong region. Very minimal clamping relative to the cutting forces can create safety concerns where the part can get swung and rapidly knocked out of place.

*Identification:* Bump the stock with a rubber mallet, the stock should not visibly move. Identify the contact interface of the stock.

*Mitigation:* Firmly clamp two sides of the stock or at least 3 contact points for cylindrical parts.

*Common Cause:* Insufficient clamping can occur for a variety of reasons and there is no unanimous common cause. When cutting, the stock material acts as a moment arm between the endmill and the fixture. The distance between the endmill and where pressure is applied is often not considered for increasing the load on the clamping mechanism.

The VR environment in Figure B.2 shows a case of 2 point contact of a cylinder and the jaws of the vice. The two point contact does not constrain the cylindrical stock material with insufficient contact.

The video includes an illustration of improper fixturing and the Figure 4.7 shows the process of
Figure 4.6: VR Illustration of Insufficient Clamping mitigation for the error case.
Parallelism Errors

A parallelism error occurs when faces of stock material are not seated flush. Skewed material will not maintain parallel references throughout the part.

Impact: The impact of this error will be greatest on a part with multiple operations. Faces may not be perpendicular and other features will shift if origin references transfer in subsequent operations. Additionally, portions of material may not be machined.

Identification: Visually inspect the angle of the stock material when placed in the fixture.

Mitigation: Clean the stock material and the fixture of any debris that could offset the part. Use parallels in the vice and tap downward with light pressure applied to fully seat the material.

Common Cause: This error is often caused by machining chips creating a displacement between the stock and vice. Additionally, not using parallels or parallel references to properly seat on will result
in parallelism errors.

![Parralelism Error](image)

**Figure 4.8: Video Illustration of Parallelism Error**

**Work Coordinate System Alignment Errors**

**Orientation Error**  An orientation error occurs when the stock material is positioned in a different orientation than prescribed in the Computer Aided Machining program.

*Impact:* Incorrectly orienting the stock material will result in machining into the fixture or other features already machined. A portion of the machining operation may be on the stock but some portions may be off the material.

*Identification:* Jog the machine to the boundaries of the tool path, above the part. If the endmill is
directly above the material and then travels off, the orientation was incorrect. 1. Raise the tool several inches above the stock and well above the fixture 2. Set Z zero above the part 3. Run the program above the stock. If the tool goes from over the material to beyond the boundary, the workpiece orientation was incorrectly established.

*Mitigation:* Visually verify the CAM maps to the setup. Correct by performing identification process, reorient, redefine Work Coordinate System origin.

*Common Cause:* This error commonly occurs when stock is affixed to the milling machine without consideration of the programmed WCS and the stock is placed in a random orientation.

![Figure 4.9: VR Illustration of Orientation Error](image-url)
Incorrect Corner for WCS Origin  The work coordinate system was established on a different corner of the stock than established in the CAM program.

Impact: The impact of selecting an incorrect corner for the WCS origin will depend on the selected corner and the WCS defined in the CAM program. The tool may crash into the fixture & break the tool or the machine will not engage with material and cut above or to the side of the material.

Identification: Travel to X0 Y0 at a height above the part. Verify tool location matches the CAM
origin. To the side of the material and fixture, travel to the Z0 position. Verify the height is at the desired Z height from the WCS origin.

**Mitigation:** Perform error ID process, redefine WCS origin through edgefinding and tool setting process if difference exists.

**Common Cause:** This error commonly occurs when edgefinding an arbitrary corner without consideration to the programmed WCS.

![Figure 4.11: VR Illustration of Incorrect Corner Selection](image-url)
**Z Zero Reference Error:** The Z Zero Reference Error is when a different Z height is defined as the WCS origin Z plane.

*Impact:* The milling machine will rapidly travel into the stock and into the workholding or the program will run above the stock material.

*Identification:* In a region free of material or fixtures, travel to Z0 after establishing. Verify tool height matches CAM program.

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Figure 4.13: VR Illustration of Z Zero Reference Error

Figure 4.14: Video Illustration of Z Zero Reference Error

**Tool Setting Errors**

**Incorrect Tool** Incorrect tool error is when a different tool is loaded in the tool holder than specified in the CAM program.
Impact: Machined portions will have a different geometry than planned. If the tool is smaller than programmed, the outer features will be larger and inner features will be small and vice versa for a larger tool.

Identification: Measure the features of machined components and evaluate deviation.

Mitigation: Prior to milling, measure the tool and note the number of flutes, type and the diameter and length. Validate that they are represented correctly in the CAM tools.

Common Cause: A common cause of incorrect tool usage is failing to change the tool if the tool change is manual.

Figure 4.15: VR Illustration of Incorrect Tool Error
Incorrect Tool Length Data  Incorrect Tool Length Data occurs when the tool length offset is different than physically measured.

**Impact:** If real tool length is less than the offset, the tool will be in the cut air. If the real tool length is longer than the offset, the tool will crash into the part or take a larger cut than expected. Depending on the magnitude of the error, the tool may also crash with the table or fixture under the stock. The part will also be the difference in length smaller.

**Identification:** When tool is created or modified: 1. Move the tool to a given Z position well above the table/established Z0 position. 2. Compare the distance between Z0 reference and the tool. Values should be equal, if correct.

**Mitigation:** Validate existing tool length offset values through measurement prior to running the CNC program.
Common Cause: Adjustments to the tool require the tool length to be updated, updating the TLO is often forgotten. Measurement errors also are cause for incorrect values.

Figure 4.17: Video Illustration of Incorrect Tool Length Error

Figure 4.18: Video Illustration of Incorrect Tool Length Error
4.2.2 Error Management Practice

Practice is a critical component of training and error management theory depends on practicing trainee familiarity with given areas to strengthen their ability to identify the presence of the error and troubleshooting skills to resolve them prior to significant impact. This work extends the methodology and framework proposed in the existing body error management curriculum design employed in surgery training [44]. The structure of error management training begins with the introduction and explanation of errors as previously outlined, followed by the practice of identification and discussion on correction. The practice phase of error identification presents 9 realistic setups, which include specifically designed components with an accompanying CAM program with toolpath and origin triad visualizations. Each of the 9 cases have at least 1 set up error present. Students are able to inspect the virtual setups for errors and are prompted to classify the errors they believe are present. Following the classification practice, the trainees are provided automatic feedback on the accuracy of their selections as shown in Figure: 4.20.
CHAPTER 4. TRAINING CONTENT DESIGN

Figure 4.19: Error Classification Module

Figure 4.20: Identification Report Card
Chapter 5

User Study Design

Evaluation of the Error Management training required a preliminary user study to be conducted to determine if the utilization of an error management curriculum would show benefits for CNC machining set up. The use of error management training for traditional machining training has not been previously studied and its impact remains unknown. This work presents the initial implementation of a VR system with an error management training philosophy. In an attempt to isolate the impact of error management from the change of mediums between a traditional training and virtual reality system, the study will evaluate and compare against 3 training conditions. The three training conditions studied are a video based procedural training, a video based procedural training with the inclusion of an error management module, and the VR error management training. Traditional CNC milling education is conducted through instructor procedure demonstration and explanation. For this work, a video procedural demonstration has been filmed for consistency.
across all participants. The difference in mediums that a traditional training are conducted in and the nature of the video procedural training that this work utilizes is acknowledged. Traditional instructor training is limited by machine availability and viewability therefore, it is assumed that the procedural video has sufficiently mitigated this difference by providing close-in views from various angles in the training video.

In summary, this study evaluates three training conditions:

- **Condition 1**: Video-Based Procedural Instruction
- **Condition 2**: Video-Based Procedural Instruction & Error Management Training
- **Condition 3**: VR-Based Procedural Instruction & VR Error Management Training

### 5.1 Participant Recruitment

The study design aims to serve as an initial investigation to provide insights on the effectiveness of error management training in VR and develop an understanding of user perception and experience with error management content in virtual reality for industrial tasks like CNC machining training. Therefore, this study aims to gather an initial sample for each training condition. Each training condition was conducted with 5 participants, totalling in 15 participants in the user study. Participants were recruited, with RIT IRB approval, to simulate an authentic training experience that could scale to other novice trainees with minimal prior training experience. The following
criteria must be satisfied in order to participate and the requirements were communicated during the recruitment process.

1. No CNC Milling Machine Experience Minimal to No

2. Experience with Machining Equipment (not eligible if enrolled in machining course)

3. Ability to Use Virtual Reality Headset

The participants recruited consisted of 11 participants that identified as male and 4 participants identified as female. Participants were recruited from the university community and the subset is influenced in age and educational background. The participants ranged from 18 to 31 in age.

Participants’ educational attainment varied as shown in Table 5.1 and Figure: 5.1 with 40% of participants having not completed any education beyond high school. Four of the 6 participants with high school diplomas have completed less than 1 semester of college education.

<table>
<thead>
<tr>
<th>What’s your highest level of education?</th>
<th>Count</th>
</tr>
</thead>
<tbody>
<tr>
<td>Associate’s degree</td>
<td>1</td>
</tr>
<tr>
<td>Bachelor’s degree</td>
<td>4</td>
</tr>
<tr>
<td>High school diploma</td>
<td>6</td>
</tr>
<tr>
<td>Master’s degree</td>
<td>4</td>
</tr>
<tr>
<td>Grand Total</td>
<td>15</td>
</tr>
</tbody>
</table>

Table 5.1: Participant Highest Educational Achievement Table

Given the internal university recruitment process, the majority of students are pursuing engineering or a computer & software engineering program. Participant degree programs are outlined below in Table: 5.2.
### Table 5.2: Participants Field Of Study

<table>
<thead>
<tr>
<th>Participant</th>
<th>Degree Program/ Major</th>
</tr>
</thead>
<tbody>
<tr>
<td>P1</td>
<td>Automotive Engineering</td>
</tr>
<tr>
<td>P2</td>
<td>Mechanical Engineering</td>
</tr>
<tr>
<td>P3</td>
<td>Non-student</td>
</tr>
<tr>
<td>P4</td>
<td>Computer Science</td>
</tr>
<tr>
<td>P5</td>
<td>Mechanical Engineering</td>
</tr>
<tr>
<td>P6</td>
<td>Human Computer Interaction</td>
</tr>
<tr>
<td>P7</td>
<td>Color Science</td>
</tr>
<tr>
<td>P8</td>
<td>School of Individualized Study</td>
</tr>
<tr>
<td>P10</td>
<td>Human-Computer Interaction</td>
</tr>
<tr>
<td>P11</td>
<td>Computer and Information Science</td>
</tr>
<tr>
<td>P12</td>
<td>Industrial Engineering</td>
</tr>
<tr>
<td>P13</td>
<td>Computer Science</td>
</tr>
<tr>
<td>P14</td>
<td>Electrical engineering technology</td>
</tr>
<tr>
<td>P15</td>
<td>Mechanical Engineering</td>
</tr>
<tr>
<td>P16</td>
<td>Computing and Information Sciences</td>
</tr>
</tbody>
</table>
Note: It is known that Mechanical Engineering & Industrial Engineering students are required to complete machining coursework. Participants involved in the study confirmed and verified that they have not participated in such coursework yet.

5.1.1 VR Experience

Ability to use VR systems is criteria for participation, however, the familiarity with V.R systems is not controlled during the recruitment process. Following the results of the pre-survey which indicated experience, participants were assigned to a training condition. Expert VR users and users with no virtual reality familiarity were involved in the evaluation of the virtual reality system. Participants’ VR familiarity is ranked 1 to 5, where 1 represents no exposure and 5 is expert, frequent user and are shown in Table: 5.3
Table 5.3: Participants Field Of Study

<table>
<thead>
<tr>
<th>Participant ID</th>
<th>VR Familiarity</th>
</tr>
</thead>
<tbody>
<tr>
<td>P1</td>
<td>2</td>
</tr>
<tr>
<td>P2</td>
<td>1</td>
</tr>
<tr>
<td>P3</td>
<td>1</td>
</tr>
<tr>
<td>P4</td>
<td>5</td>
</tr>
<tr>
<td>P5</td>
<td>3</td>
</tr>
<tr>
<td>P6</td>
<td>3</td>
</tr>
<tr>
<td>P7</td>
<td>1</td>
</tr>
<tr>
<td>P8</td>
<td>2</td>
</tr>
<tr>
<td>P10</td>
<td>4</td>
</tr>
<tr>
<td>P11</td>
<td>1</td>
</tr>
<tr>
<td>P12</td>
<td>2</td>
</tr>
<tr>
<td>P13</td>
<td>2</td>
</tr>
<tr>
<td>P14</td>
<td>3</td>
</tr>
<tr>
<td>P15</td>
<td>3</td>
</tr>
<tr>
<td>P16</td>
<td>5</td>
</tr>
</tbody>
</table>

Table 5.4: VR Background Summary Table

<table>
<thead>
<tr>
<th>Virtual Reality Experience</th>
<th>Participant Count</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 (No Experience)</td>
<td>4</td>
</tr>
<tr>
<td>2</td>
<td>4</td>
</tr>
<tr>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>4</td>
<td>1</td>
</tr>
<tr>
<td>5 (Expert)</td>
<td>2</td>
</tr>
</tbody>
</table>

5.2 Materials & Equipment

CNC machining requires substantial investment in equipment and tools. The evaluation of the training systems utilize real physical equipment to evaluate how the training designs transfer to
realistic operating environments.

5.2.1 Training Equipment:

The video based training is accessible from any internet enabled device capable of streaming from Google Drive. The study was administered on a 15” laptop. The virtual reality training was conducted using an Oculus Quest 2 headset and Touch controllers. The training requires a computer with a dedicated graphics card capable of supporting Unity 3D VR. The study was conducted from a laptop for graphics processing and a connected Quest headset.

5.2.2 Evaluation Equipment

The evaluation was conducted on a Tormach 1100 CNC milling machine, identical to the virtual reality training model. During the evaluation, trainees have to demonstrate an ability to identify the proper fixture, endmill, and stock material to complete the task. The task is prepared with an assortment of fixturing options including clamping straps/blocks and a vice.

Table 5.5 Note: * Indicates tools or equipment where supplemental instruction was provided orally prior to the start of the evaluation. ** Metal chips should be applied to the selected fixture in order to evaluate procedural fixture cleaning knowledge.
<table>
<thead>
<tr>
<th>Tool/Material</th>
<th>Function</th>
</tr>
</thead>
<tbody>
<tr>
<td>CNC Milling Machine</td>
<td>All Functions</td>
</tr>
<tr>
<td>Clamping Blocks</td>
<td>Fixture Selection</td>
</tr>
<tr>
<td>Vice</td>
<td>Fixture Selection</td>
</tr>
<tr>
<td>Paper</td>
<td>Z Zero &amp; Tool Touch Off</td>
</tr>
<tr>
<td>Edge Finder</td>
<td>X &amp; Y Work Coordinate Definition</td>
</tr>
<tr>
<td>Tool Touch Off Setter</td>
<td>Z Zero &amp; Tool Touch Off</td>
</tr>
<tr>
<td>Assorted End Mills</td>
<td>Tool Identification &amp; Tool Touch Off</td>
</tr>
<tr>
<td>Tool Holder &amp; Collet*</td>
<td>All Tool Usage</td>
</tr>
<tr>
<td>Brush</td>
<td>Fixture Process</td>
</tr>
<tr>
<td>Metal Chips/Debris**</td>
<td>Fixture Process</td>
</tr>
<tr>
<td>Measuring Tape*</td>
<td>Stock Material ID</td>
</tr>
<tr>
<td>Digital Calipers*</td>
<td>Stock Material ID &amp; Tool ID</td>
</tr>
<tr>
<td>CNC Jogging Control*</td>
<td>All Machine Motion</td>
</tr>
</tbody>
</table>

Table 5.5: Required Equipment for Task Evaluation

5.3 Environment

The training portions of the study were conducted in a classroom environment where the trainee could watch training videos. The VR training was conducted in a classroom setting where ample space had been provisioned and cleared in order to create a safe environment for participants. The researchers monitored the activity of participants during the training and recorded the training process. The researchers were available during the training to answer questions, with limited scope in order to reduce variation across each training condition. During the VR training, the researchers monitored the activity inside the training through an external display showing the scene and the trainees point of view.

The evaluation of the training programs occurred on real CNC machines for realism. The CNC milling machine used for evaluation was located in the university makerspace. Evaluations were
conducted during a reserved time frame. The environment and hands on evaluation aims to add authenticity to a practical machining environment where the training system could be deployed.

5.4 Study Procedure

The study procedure is broken down into three primary phases including training, evaluation, and post-evaluation feedback consisting of a questionnaire & interview. The user study procedure is standardized and administered from the User Study Administration Guide which outlines the process for the session and provides researchers a consistent script. The User Study Administration Guide can be found in the Appendix. Prior to any training or evaluation, users are introduced to the work and complete an Informed Consent form, per the IRB requirements. Following
participants’ introduction to the flow of the sessions, they will begin the training portion.

During the training process, all participants are limited to a training session of 45 minutes. The video based training contains 20-30 minutes of content. Review of the material is permitted. VR training sessions are also limited to 45 minutes for consistency and to prevent major eye strain or motion sickness which is not uncommon with VR usage. During the introduction, VR condition trainees are informed they can pause and resume or end the session at any time if they feel sick. Following the training, participants are provided an opportunity to take a break for 15 minutes prior to initiating the evaluation.

The evaluation process of the session follows the completion of a task, participants are prompted to “Complete the setup of the CNC milling machine given the material and tool information, the toolpath visualization and CAM program that identifies the work coordinate system and all provided equipment. All tools, materials and information are contained on the table or in the Machine Set Up Task packet. The Machine Set Up Task packet can be found in the Appendix. During the evaluation process, two researchers are present. One researcher is a designated observer documenting and noting details of the completion of the task and errors, omissions, and corrections to the procedure. Errors are logged at the completion of the task. Expanded details of the data collection process and content are outlined in the following subsection.

Once the trainee indicates they have completed the task to their extent, the participant will complete a post-evaluation feedback questionnaire. The questionnaire captures NASA TLX
questions followed by a series of likert-styled qualitative questions. After completing the questionnaire, an unstructured interview is conducted with the participant and researchers to gain additional insights on their experience. The interview concludes the user study session.

5.5 Data Collection

The data collection for this work begins prior to the study training sessions in order develop an understanding of potential participants backgrounds and eligibility. Prospective participants are asked to complete a pre-survey during the registration process and demographic information and experience information is collected. The majority of data collection is driven from the evaluation phase.

During the evaluation task, participants are filmed for analysis and verification after the session. Performance behavior is recorded throughout the session. Drawing from the instructional content, a procedure and subset of tasks have been compiled. For each procedural step, the observer is logging if the student asks a question, if they deviate from the process, if corrections are made, or if they entirely miss the step, in addition to correctly executing the step.

A sample of the Evaluation Sheet is shown below in Table: 5.6. The full Evaluation Sheet can be found in the Appendix A.
The 5 categories noted in the Evaluation Table represent the variety of paths a trainee can navigate the setup process. If a participant asks a question regarding a specific step in the process a tally is marked for the process step. The “Deviated” category aims to capture sequential deviations. For example, a participant may begin the edge finding process to establish the X and Y origins prior to loading the edge finder into the tool holder. If the student realizes the procedural mistake and later loads the tool, this will be documented as Deviated and Corrected. In the case the technique deployed by the participant is incorrect and then adjusted to follow the proper technique, in sequence, this will be documented as only “Corrected”. The “Missed” category represents total omissions in the procedure. Correct completion of technique and sequence on the participants first attempt at the task is logged as “First Pass Correct”. In addition to the tabulation of procedural performance, the final set up is evaluated for the presence of errors. If any of the errors outlined in the Error Management Section 4.2.1 were made, they are recorded.

Retrospectively, the video is reviewed to verify question count and validity of the data. in order to improve the quality of the observers observation sheet. Furthermore, the duration for task completion is recorded from timestamps when the participant begins and ends the activity. The activity data collection concludes the quantification of participant performance and applied
training effectiveness.

Following the task evaluation, participants complete a post evaluation questionnaire regarding their experience and perception of the training and task. The contents of the Post-Evaluation Questionnaire can be found in the Appendix. The post questionnaire captures NASA TLX based questions in order to determine the cognitive load of the evaluation. Following the NASA TLX questions, 11 targeted questions are asked on a 5 point Likert scale to advance the understanding of the user experience during the training process.

At the conclusion of the user study, the participants discuss their experience with the training and evaluation in a dialogue with the researchers. The discussion is unstructured and researchers asked a variety of questions, some standardized and other relating to the specific performance of the participant. The discussion is recorded for reference. Notes and commentary from participants are recorded to inform future system design and advance a holistic understanding of the training.
Chapter 6

Results

6.1 Evaluation Performance

The evaluation derived results based on participants performance is evaluated in the following section. Table: 6.1 presents a summary of each participant’s performance. The raw data for the entire procedure has been totaled for each participant. A total of 21 procedural steps and actions are totalled for each of the evaluation criteria per participant. The full procedure and evaluation can be found in Appendix A: Evaluation Sheet.
<table>
<thead>
<tr>
<th>Group</th>
<th>Participant</th>
<th>Completion Time</th>
<th>Questions</th>
<th>Deviated</th>
<th>Corrected</th>
<th>Missed</th>
<th>FP Correct</th>
</tr>
</thead>
<tbody>
<tr>
<td>Video</td>
<td>P1</td>
<td>1854</td>
<td>0</td>
<td>3</td>
<td>3</td>
<td>2</td>
<td>11</td>
</tr>
<tr>
<td></td>
<td>P2</td>
<td>1854</td>
<td>4</td>
<td>2</td>
<td>0</td>
<td>2</td>
<td>15</td>
</tr>
<tr>
<td></td>
<td>P3</td>
<td>2259</td>
<td>13</td>
<td>1</td>
<td>1</td>
<td>3</td>
<td>13</td>
</tr>
<tr>
<td></td>
<td>P4</td>
<td>1514</td>
<td>4</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>14</td>
</tr>
<tr>
<td></td>
<td>P10</td>
<td>2505</td>
<td>1</td>
<td>3</td>
<td>3</td>
<td>2</td>
<td>14</td>
</tr>
<tr>
<td>Video &amp; EM</td>
<td>P5</td>
<td>1167</td>
<td>0</td>
<td>4</td>
<td>1</td>
<td>0</td>
<td>15</td>
</tr>
<tr>
<td></td>
<td>P6</td>
<td>1810</td>
<td>4</td>
<td>1</td>
<td>1</td>
<td>6</td>
<td>14</td>
</tr>
<tr>
<td></td>
<td>P7</td>
<td>1874</td>
<td>4</td>
<td>6</td>
<td>6</td>
<td>1</td>
<td>11</td>
</tr>
<tr>
<td></td>
<td>P8</td>
<td>1387</td>
<td>0</td>
<td>3</td>
<td>3</td>
<td>0</td>
<td>13</td>
</tr>
<tr>
<td></td>
<td>P11</td>
<td>1560</td>
<td>0</td>
<td>4</td>
<td>3</td>
<td>0</td>
<td>13</td>
</tr>
<tr>
<td></td>
<td>P12</td>
<td>1560</td>
<td>0</td>
<td>4</td>
<td>4</td>
<td>1</td>
<td>14</td>
</tr>
<tr>
<td></td>
<td>P13</td>
<td>2220</td>
<td>9</td>
<td>2</td>
<td>2</td>
<td>0</td>
<td>18</td>
</tr>
<tr>
<td></td>
<td>P14</td>
<td>751</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>6</td>
<td>12</td>
</tr>
<tr>
<td></td>
<td>P15</td>
<td>869</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>18</td>
</tr>
<tr>
<td></td>
<td>P16</td>
<td>1019</td>
<td>5</td>
<td>0</td>
<td>0</td>
<td>8</td>
<td>12</td>
</tr>
</tbody>
</table>

Table 6.1: Summary Participation Performance Data
Participant task completion time from Table: 6.1 is grouped by training condition and the average completion times are shown in Table: 6.1. The trend in Table: 6.1 indicates a reduction of task completion time with the introduction of error management training and Virtual Reality Error Management with the participants from the baseline video training completing the task in an average of 1997.2 seconds. Average completion times for the Video & EM and Virtual Reality with EM are 1559.6 and 1283.8 seconds representing a 21.9% and 35.7% decrease respectively.

Figure 33: Completion Time for Training Conditions

Completion time is not a holistic measure of training performance and as was previously discussed prior, errors can occur procedurally and systematically. Table 6.2 shows participants who received the Video & Error Management were asking fewer questions than the other conditions with 1.6 questions on average as compared to 4.4 and 3 questions for Video only & VR respectively. Participants from the Video & Error Management training on average made more deviations/mistakes and identified them with corrections as shown with an average number of deviations at 3.6. Video & Error Management participants made equal corrections which corresponded to each deviation as seen in Table: 6.1 with the exception of P11. Participants from the VR with Error Management, on average, completed 1.5 more procedural steps correctly on the first pass through the task evaluation.

Performing a procedure does not indicate that the machining set up has been properly therefore it was imperative to evaluate the completed setup. Table 8 shows the total number of set up errors
Table 6.2: Average Procedural Performance Indications for Training Condition

<table>
<thead>
<tr>
<th></th>
<th>Question</th>
<th>Deviated</th>
<th>Corrected</th>
<th>Missed</th>
<th>FP Correct</th>
</tr>
</thead>
<tbody>
<tr>
<td>Video</td>
<td>4.4</td>
<td>2</td>
<td>1.6</td>
<td>2.2</td>
<td>13.4</td>
</tr>
<tr>
<td>Video &amp; EM</td>
<td>1.6</td>
<td>3.6</td>
<td>2.8</td>
<td>1.4</td>
<td>13.2</td>
</tr>
<tr>
<td>VR w/ EM</td>
<td>3</td>
<td>1.6</td>
<td>1.6</td>
<td>3</td>
<td>14.8</td>
</tr>
</tbody>
</table>

based on the previously defined categories for each training condition. During the evaluation, participants successfully avoided making mistakes related to Fixture Selection & Tool Setting. Participants who received the video training only made the largest amount of errors with all but one participant making a Wrong Origin Corner error and all participants incorrectly oriented the stock material. The introduction of the error management module slightly reduced the total number errors with a reduction of 1 error in both Corner & Orientation cases. The VR with Error Management trained participants were found to correctly select the proper and corner and orient the stock material with a total of 2 participants making corner and orientations errors. Additionally, Participants 7 & 8 identified errors after they had completed the procedure and then adjusted accordingly. P8 identified and corrected an orientation error and participant 7 corrected a WCS Corner Error. The methods for identification utilized by the two participants mapped to guidance from the error management training.
6.2 Post Study Survey Results

Following the evaluation phase of the study, data was collected regarding the participants’ experience during the training and their overall perception of the training and evaluation. The data collected following the evaluation performance is presented in this section. In order to understand the mental workload of the participants, the questionnaire included the NASA TLX. This work presents a Raw NASA TLX and the scores are unweighted. The NASA TLX understands workload through 6 primary categories with questions to address the demand of the task. The questions and survey format are as follows:

Mental: How mentally demanding was the task? (1-very low, 10-very high)

Physical: How physically demanding was the task? (1-very low, 10-very high)

Temporal Demand: How hurried or rushed was the pace of the task? (1-very low, 10-very high)

Effort: How hard did you have to work (mentally and physically) to accomplish your level of performance? (1-very low, 10-very high)

Performance: How successful were you in accomplishing what you were asked to do? (1-high
satisfaction, 10-very low success)

Figure 6.1 is compiled as an average score by training condition. The full raw data can be found in Appendix B. The mental load for both video conditions have an average score 5.4 and the VR participants rate a workload of 6.4. The frustration expressed by VR participants is higher than the video methodologies with an average value of 4.6. The Video based conditions on average were rated a 2.8 for Frustration.

![Raw NASA TLX Scores by Training Condition](image)

Figure 6.1: Raw NASA TLX Workload by Group
Table 6.4: Raw NASA TLX Average Workload by Group

Following the NASA TLX questionnaire, participants were asked subjective questions regarding their perception and general experience during the session. Questions were asked on a 5 point scale and average responses are shown in Table: 6.5. Table: 6.5 is color coded blue to indicate the most favorable score in the conditions. The Table: 6.5 shows Virtual Reality participants reported on average higher engagement with a score of 4.4 in comparison to the Video based methodologies which rated 4. Participants from the VR training also reported that they were not easily distracted during the training as indicated by an average score of 1.8 indicating somewhat disagreeing with the statement while participants from Video Only & Video & EM reported a scores of 2.8 and 2.4 respectively. Additionally, VR participants responded with a lower score to the “need to ask questions when manipulating CNC machines”. Video conditions reported an average of 4.6 for both Video conditions while VR participants reported a score of 3.6. Lastly, the introduction of the error management content impacted the perceived helpfulness of the training. Video Only, Video & EM
and VR participants reported scores of 3.4, 3.6, 4.2, respectively to “the proposed strategy is helpful for CNC machine set-up”.

<table>
<thead>
<tr>
<th>Please rate how much do you agree with this statement: 1: Strongly Disagree 5: Strongly Agree</th>
<th>Traditional</th>
<th>Traditional + Error</th>
<th>VR</th>
</tr>
</thead>
<tbody>
<tr>
<td>“I feel the instruction content in the proposed learning strategy was very clear to understand”</td>
<td>3.8</td>
<td>3.6</td>
<td>3.2</td>
</tr>
<tr>
<td>“I fully engaged in the instruction content through the proposed learning strategy”</td>
<td>4</td>
<td>4</td>
<td>4.4</td>
</tr>
<tr>
<td>“I feel confident with working on coordinate system alignment (x,y,z axis offset) after receiving training.”</td>
<td>3.8</td>
<td>4.2</td>
<td>3.2</td>
</tr>
<tr>
<td>“I feel confident with fixturing selection after receiving training.”</td>
<td>3.6</td>
<td>3.2</td>
<td>3.8</td>
</tr>
<tr>
<td>“I feel confident with tool offsetting after receiving training.”</td>
<td>3.6</td>
<td>3.6</td>
<td>3.8</td>
</tr>
<tr>
<td>“I can easily notice the potential errors while setting up the machine,” e.g. wrong orientation, wrong tools</td>
<td>3.2</td>
<td>3</td>
<td>3.4</td>
</tr>
<tr>
<td>“I feel easily distracted and get lost through the proposed learning strategy.”</td>
<td>2.8</td>
<td>2.4</td>
<td>1.8</td>
</tr>
<tr>
<td>“I feel the proposed strategy is helpful for CNC machine set-up”</td>
<td>3.4</td>
<td>3.6</td>
<td>4.2</td>
</tr>
<tr>
<td>“I feel the need to ask questions from an in-person tutor while manipulating the CNC machine.”</td>
<td>4.6</td>
<td>4.6</td>
<td>3.6</td>
</tr>
<tr>
<td>“I have strong safety concerns while manipulating the CNC machines.”</td>
<td>2.2</td>
<td>3</td>
<td>2</td>
</tr>
</tbody>
</table>

Table 6.5: Qualitative Experience Summary by Training Type
Chapter 7

Discussion

The objective of this thesis work is to evaluate the effectiveness of an error management approach training in Virtual Reality as applied to CNC milling machine set up processes. The literature has demonstrated great interest in utilizing virtual reality for CNC simulation and demonstrated success in operational feature reproduction however limited investigation to training efficacy has been conducted. Given the availability of affordable virtual reality hardware like the Oculus Quest 2, the research question for VR CNC training should no longer remain a matter of technical feasibility but one where the nuance of machining training and XR are refined to deliver an optimal and effective training. This work aimed to explore such training optimization explorations with the introduction of a novel error management training to CNC machining and implemented the training in an immersive environment.
CHAPTER 7. DISCUSSION

The VR error management training has demonstrated its benefits and through the investigation and evaluations, further opportunities have been identified through the analysis of performance data and participant feedback. The reduced task time, fewer questions, reduction of total errors and presence of effective error identification indicate benefits from the system however other results indicate a focus area for future work.

Table 6.2 indicates that the participants in the VR training participants are omitting steps from the process at a greater rate than the video based methodologies. Video participants on average omitted 2.2 steps and the video and EM participants omitted 1.4 steps while the VR group on average omitted 3 steps. This discrepancy was largely driven by 2 participants however it highlights the procedural training in VR as an area of opportunity. The procedural training for VR was designed to emulate modeling a demonstration and the demonstration was accomplished using spatial animations and audio and text aided by a variety of other visual aids. Participant 14 expressed in the follow up interview a “difficult to recall the procedure” and “issues with short term memory”. The participant spent the majority of the training time in the practice portions identifying errors and performing corner selections because “repeated practice is . . . good for getting that info to stick”. In order to improve the efficacy of the procedural training in VR, increasing the opportunities to interactively practice the process is suggested given the feedback and data on VR participants omitting steps of the process. Participants in the Video & Error Management training omitted on average 1.4 steps and Video Only Participants omitted 2.2. The
increase of omissions in VR with EM and decrease with Video & EM, from the Video only baseline suggest that the Virtual Reality design is attributable for the increase.

In the evaluation of completed fixturing, a trend emerged in participant performance where none of the participants made a fixturing or tool setting error. The design of the evaluation task may be an overly contributing factor, see Appendix A: Task for part details. The evaluation task follows the design of a simple part with an internal pocket and external contour. The part was designed to be simple given the introductory nature of the training however the design may be influencing participants to unintentionally avoid Fixturing Errors. The part can successfully be machined using a vice which was robustly demonstrated in all training sessions. Alterations to the part complexity used for evaluation may introduce a greater prevalence of fixturing errors. Future investigations to task design and their influence on performance would be necessary.

Through the process of the user study task evaluation, a trend emerged amongst participants in their decision making process while completing the task. Participants from the Video Procedure condition frequently oriented the stock material and selected the Work Coordinate System shown in the instructional video even though participants were instructed to align coordinate systems based on the specific CAM program and provided material indicating a different configuration. Three of the five participants explicitly stated they were “copying what was in the video” in the follow up interview. The trend of copying the instruction indicates the importance of training with the inclusion of context for decision making. Building context and providing justification around
the impact of decisions is a core component of the error management training structure and is likely responsible for shifting participant mindset when performing the task.

From Table: 6.3, it is clear that the spatial nature of virtual reality impacts the ability to effectively communicate errors that are spatial in nature like the orientation and corner error. The reduction of highly prevalent errors like Incorrect Orientation for participants who are trained with the VR & Error Management justifies the value presented by training in virtual reality however the use of virtual reality as a training medium is not without other implications. Virtual Reality is commonly found to be nauseating and causes motion sickness. No participants expressed discomfort during the training however it is recognized that due to the length of the training session (45 minutes maximum), participants may begin to feel motion sick and scaling the training may require modifications to the administration of the session. Furthermore, given that VR is just now beginning to see large-scale adoption, familiarity with the training medium is new in comparison to video based methods and given the demographics (college students; ages 18-30) of all participants, they have a high degree of familiarity with learning from videos. This degree of system unfamiliarity begins to explain the higher metal work load shown in Figure 34. The NASA TLX raw data indicates a higher mental mental demands and level of frustration. Inherent in the learning process are mental demands that are beneficial for skill development. Cognitive Load Theory suggests three forms of cognitive loads are intrinsic, extraneous and germane cognitive loads. Intrinsic cognitive load represents the complexity of content and information. Extraneous loads are those unrelated to
CHAPTER 7. DISCUSSION

the actual process of learning but influence the mental requirements and access to the information. Finally, germane cognitive load is classified as the load required to process new information and connect concepts impacting new information. Germane cognitive load is commonly understood as the load that takes place when an individual is actually learning. Given that an increase in germane cognitive load would indicate an effective training procedure, it is difficult to conclude the increase seen in the raw NASA TLX data. Future work is required to characterize the increase in Mental Workload however, the increase could be attributed to participants learning how to navigate the virtual reality environment. The system navigation using the raycast laser cursor and buttons on the controller influence the training throughout and is compared to a passively observable video. The extrinsic cognitive workload is likely higher as a result.

The NASA TLX also indicates a higher level of frustration (insecure, irritated, stressed, annoyed) than the video based systems seen in Figure: 6.1. Participants’ background and expectations of the system are believed to be the influential factors for the higher average Frustration score for the participants. The participant frustration score and and VR familiarity are shown below:

<table>
<thead>
<tr>
<th>How insecure, discouraged, irritated, stressed, and annoyed were you? (1- no frustration, 10- extremely frustrated)</th>
<th>How would you describe your level of experience and familiarity in the Virtual Reality system? (1- no experience, 5-expert familiarity)</th>
</tr>
</thead>
<tbody>
<tr>
<td>P12 4</td>
<td>2</td>
</tr>
<tr>
<td>P13 8</td>
<td>2</td>
</tr>
<tr>
<td>P14 4</td>
<td>3</td>
</tr>
<tr>
<td>P15 2</td>
<td>3</td>
</tr>
<tr>
<td>P16 5</td>
<td>5</td>
</tr>
</tbody>
</table>

Table 7.1: Frustration and Experience Comparison
P13 and P16 frustrations scores are of note due to their high value. In the interview following the evaluation, P13 expressed concern about training completion: “I was worried about what I missed mostly because I ran out of time”. Given the 45 minute training constraint, P13 did not complete the entirety of the training and as a result their concern manifested as stress and insecurity. P16’s background in VR with daily usage informs their expectations on how the system is going to operate. In the follow up interview, P16 provided suggestions for VR interface design and suggestions for standardizing with current trends. The divergence of the system and best of class VR interface design increased points of irritation leading to a higher Frustration score.

Through analysis of the system with a deepened understanding from users, the following recommendations are made for future training systems utilizing Virtual Reality:

1. Guide participants through procedures in 1st person

   - Participants overwhelmingly expressed an appreciation of the portions of the training that were highly interactive like the Corner Selection process. The 1st person guided action is a form of practice.

   - Perspective Translation: Participants mentioned rewatching animations in order to understand how they would perform the task. Several VR participants mentioned that they felt comfortable with the procedure in VR and then were less confident when they had to perform the task themselves.

2. Contextualize visual aids
Onboarding users to understand what visual aids imply will eliminate users from building mental models on their reason.

Users found attention aids and virtualized concepts like work coordinate system and toolpaths to be very helpful but asked for clarification during the training sessions.

Given the learnings from this work, future work should work to implement the design recommendations to create a robust and effective training environment. In addition, limitations of this work should be evaluated. This work focused on evaluating error management to optimize VR training to enable realistic and effective CNC machining. In order to control the scope of the research investigation, the focus of this work was on the CNC set up due to its criticality and long term necessity.

The design and methodology of the user study may also impact the long term retention and true effectiveness. This study conducted evaluations shortly after the training process however this timeline does not correlate to. Some participants mentioned that they did not feel they had sufficient time to process and let the content settle prior to evaluations. Future work should investigate the impact of time between training and evaluation. Additional investigations should evaluate the long term retention of the procedures and error identification ability.

Claims derived from findings of this work are limited given the scale of the user study and its impact on the ability to make statistically significant claims on the impact of error management
and the VR system. While we believe that 15 participants with 5 per training condition allows us to generalize learnings and inform future work relating to CNC machining training in VR, future work should increase the scale of the user studies to statistically validate the impact.
Chapter 8

Conclusion

This work aimed to advance the state of machining training through the application of error management techniques while using Virtual Reality. Principally, this work aimed to develop an understanding regarding the applicability and feasibility of error management training in the CNC machining set up environment. This study indicates that the combination of error management reduces the prevalence of spatial errors like Orientation Errors. This study also observed a decrease in task completion time for conditions implementing error management suggesting the curriculum has benefits outside of the VR domain. Participants expressed excitement toward the possibilities of machining training and were on average more engaged than video based participants. Participants also well understood and appreciated the benefits of VR allowing low risk practice. In summary, this work indicates that the trends of training improvements were validated however the work is not without limitations. Future research is required to statistically validate the initial
findings and future research can serve as an opportunity to implement the design suggestions derived from this work.

Future work may extend the training environment to represent a collaborative multi-user training system. The limitation of machining equipment could be reduced and with a full classroom of virtual machines where students can collaborate and a single instructor can support all students in the training environment. Potential opportunities for continued research are investigating the effectiveness of training with peers collaboratively or independently. A virtual training environment could support both possibilities.

Furthermore, the findings of this work indicate that 1st person guided activities are the preferred method of VR instruction. Future work could expand upon the degree of guidance provided to the user and vary the level of support as they progress through their understanding. Investigating trainees degree of guidance required to complete a given task will provide insights into the effectiveness of the training and students developments. This work will serve as a base foundation for future work integrating cognitive science and learning theory into practical training applications to support manufacturing workforce.
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Appendices
Appendix A

User Study Supporting Material

Appendix A includes User Study Supporting Material

A.1 Consent Form
TITLE OF STUDY: VR-based Machining Training compares to traditional video-based instruction

Investigators: Yunbo Zhang, Assistant Professor, Kate Gleason College of Engineering, Rochester Institute of Technology, ywzeie@rit.edu.
Matt Ryan, Master Student, Kate Gleason College of Engineering, Rochester Institute of Technology, mxr9154@rit.edu.

Purpose: The goal of this research is to evaluate different methods and educational practices for machining instruction. This research aims to help machine learners to understand the procedure for setting up CNC machines and potential errors. We will conduct a between-subjects user study in a controlled laboratory setting. One condition will be conducted through Oculus Quest 1 to provide an immersive VR training environment and another condition is training video-based instruction. The findings will inform the future design of machining training strategies especially in VR environments.

Procedure: Before the study, participants will visit the RIT C-DIME lab to attend the study, and the environment and devices will be fully sanitized according to the RIT COVID-19 protocols. Participants will also fill a short pre-study survey about their basic demographic information. The pre-study survey is estimated to take about 3 minutes to complete. At the beginning of the study, participants will be introduced to the study procedure. Meanwhile, researchers will assist participants to set up the VR headset. This preparation process is estimated to take about 5 minutes. Each participant will only experience one condition in the study.

The first condition of study will be conducted in a controlled lab environment. Participants will wear a HMD to access the virtual training environment. In the virtual training, participants will experience a virtual machine workshop which contains the simulated CNC machine, tools, parts and the main instruction panel. We will conduct the hand-on evaluation on setting up the CNC milling machine and record the entire procedure. After the experiment, we will conduct a post-study questionnaire and semi-structured interview to ask about their challenges and understanding of the proposed training strategy.

In order to compare with the traditional training strategy, each participant watches 20 minutes of CNC machining set-up tutorial video. Participants are allowed to go backward anytime in the video. The training video covers overview of workflow, fixture selection, coordinate system alignment and so on. After the video, we will conduct the hand-on evaluation on setting up the CNC milling machine and record the entire procedure. After the experiment, we will conduct a post-study questionnaire and semi-structured interview to ask about their challenges and understanding of the traditional training strategy. This study will provide a significant opportunity to advance the knowledge of improving machine training efficiency via VR. The study will be video-recorded for analysis purposes. All data will be kept confidential.

Consent Agreement for Recording: By marking or signing below, you acknowledge that the purpose and procedures for recording during this study have been described to you. You consent to allow recording during participation, and for those data to be reviewed by persons involved in the study.

________________ I give my full consent to the use of the collected data as described above.
________________ I do not agree. I will not participate in the study.

Risks: The potential risks in this project are minimal. If selected for the VR training session, you might experience slight motion sickness. For the evaluation task, you might encounter physical risks involved with operating in a machine environment like manipulating parts and tools. To protect your safety, you will be required to wear safety glasses. The facilitator will be available to assist in handling any parts and tools as
required to create a safe working environment. To protect your privacy, you should not mention your name or other personally identifiable details in the study. The text transcript of your responses during the study will become part of a permanent public dataset accessible to researchers at RIT and other institutions. Any personally identifiable information (including your name) will be removed prior to the inclusion of your data in this permanent public dataset.

**Benefits:** There are no immediate benefits to participating in this study. This research will examine the effectiveness of virtual reality training for specific machining tasks. This work may inform the future development of workforce training for machinists, which will help to bridge an expanding skills gap in the manufacturing industry. Results of this study may help develop an ecosystem for instructors and students operating machining equipment.

**Confidentiality:** Every attempt will be made by the investigators to maintain all information collected in this study confidential, except as may be required by court order or the law. Authorized representatives of Rochester Institute of Technology, including members of the Institutional Review Board (IRB), a committee charged with protecting the rights and welfare of research subjects, may be provided access to records that identify you by name.

**Costs/Compensation:** Participants will receive $20 as compensation.

**Right to Refuse or Withdraw:** Your participation is completely voluntary. You may refuse to participate or withdraw your consent or discontinue your participation in the study at any time without penalty or loss of benefits or rights to which you might otherwise be entitled.

**Termination of Participation:** If there is a technical problem during your session, the investigator may terminate your participation in the study.

**Questions:** If you have any questions about this study, you should feel free to ask them now or anytime throughout the study by contacting the principal investigator at RIT, Dr. Yunbo Zhang, Assistant Professor, Kate Gleason College of Engineering, tel. 585-475-5571, ywzeie@rit.edu.

If you have any questions regarding your rights as a participant, you can contact Heather Foti, Associate Director, Office of Human Subjects Research, Rochester Institute of Technology (RIT). Her contact number is 585-475-7673 or email hmfirs@rit.edu during normal business hours.

**What Signing this Form Means:** By signing this consent form, you agree to participate in this research project. The purpose, procedures to be used, as well as, the potential risks and benefits of your participation have been explained to you in detail. You can refuse to participate or withdraw from this research project at any time without penalty. Refusal to participate in this study or withdrawal from this study will have no effect on any services you may otherwise be entitled to from Rochester Institute of Technology. You will be given a copy of this consent form.

<table>
<thead>
<tr>
<th>Printed Name of Participant</th>
<th>Signature of Participant</th>
<th>Today's Date</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Printed Name of Investigator</th>
<th>Signature of Investigator</th>
<th>Today's Date</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
A.2 Screening Questionnaire
Machining Training Sign-up Survey

Thank you for your interest in participating in our research. This study aims to examine the efficiency of using Virtual Reality for training the set-up of CNC machines. The participation is entirely voluntary. No personally identifiable information is collected. In total, the study is expected to be around 90 - 110 minutes. Each participant will get $20 compensation after the study. It will take about 3 minutes to complete this survey. Thank you for your valuable time!

Please answer the following questions to sign up for your participation. Your responses will be collected after this form is complete. If you want to withdraw your participation, please contact Matt (mxr9154@rit.edu) or Molly (yw7615@rit.edu).

* Required

1. Your age

2. Your gender
   - Female
   - Male
   - Prefer not to say
   - Other:

3. What is/are your major(s)?
   - Check all that apply.
   - Mechanical Engineering
   - Computer Engineering
   - Bio-medical Engineering
   - Industrial Engineering
   - Chemical Engineering
   - Automation Engineering
   - Other:

4. What’s your highest level of education? 
   - Mark only one oval.
   - No formal education
   - High school diploma
   - College degree
   - Vocational training
   - Bachelor’s degree
   - Master’s degree
   - Ph.D. or higher
   - Prefer not to answer
   - Other:

5. Do you have any experience with milling machines for manufacturing? If Yes, how long? (in years)

6. Please rate your experience level with machining setup processes. E.g. fixturing, work coordinate offsetting, tool length setting
   - Mark only one oval.
   - Not familiar at all
   - Slightly familiar
   - Somewhat familiar
   - Moderately familiar
   - Extremely Familiar

7. What types of CNC machines do you use?
   - Check all that apply.
   - CNC Lathes and Turning Machines
   - CNC Milling Machines
   - CNC Laser Machines
   - CNC Electrical Discharge Machines (EDM)
   - CNC Plasma Cutting Machines
   - None of above
   - Other:

8. How often do you use Computer Numerical Controlled (CNC) machines?
   - Mark only one oval.
   - Every day or more often
   - A few times a week
   - Once a week
   - Once or twice a month
   - A few times a year
   - Never used
9. How would you describe your level of experience and familiarity with Computer Numerical Controlled (CNC) machines?*

1: Extremely poor (No experience at all) 2: Bad (Used few times before but not familiar) 3: Average (Occasionally use the system) 4: Good (Interact with the system well and use frequently) 5: Excellent (Expert in the system with a certain level of design/programming background)

Mark only one oval.

[ ] 1
[ ] 2
[ ] 3
[ ] 4
[ ] 5

10. How often do you use VR during the last year? (such as Game, Social, Video watching etc.)*

Mark only one oval.

[ ] Every day or more often
[ ] A few times a week
[ ] Once a week
[ ] Once or twice a month
[ ] A few times a year
[ ] Never used

11. Do you have motion sickness in Virtual environments or other conditions? *

Mark only one oval.

[ ] Yes, I have motion sickness using VR
[ ] Yes, I have motion sickness in other conditions
[ ] No, I don’t have motion sickness
[ ] Maybe, I am not sure

12. Is your vision normal or corrected-to-normal? *

Mark only one oval.

[ ] Yes, my vision is normal
[ ] Yes, I use contact lenses or glasses
[ ] No
[ ] Prefer not to say

13. What do you use virtual reality platforms for? *

Check all that apply.

☐ Meet and Socialize
☐ Paint and design
☐ Play Games
☐ Watch videos
☐ Other: _______________________________

14. How would you describe your level of experience and familiarity in the Virtual Reality system?*

1: Extremely poor (No experience at all) 2: Bad (Used few times before but not familiar) 3: Average (Occasionally use the system) 4: Good (Interact with the system well and use frequently) 5: Excellent (Expert in the system with a certain level of VR/AR design/programming background)

Mark only one oval.

[ ] 1
[ ] 2
[ ] 3
[ ] 4
[ ] 5

15. Please write a short description about your frequent activities in Virtual Reality *

__________________________________________________________________________
__________________________________________________________________________
__________________________________________________________________________

16. Your name

It could be your first name or your preferred name that helps us to call you

__________________________________________________________________________

17. Your email address

__________________________________________________________________________

18. Your Phone No.

__________________________________________________________________________

19. Would you like to participate in any interview or user study related to Robotic system, machining training in future? *

Mark only one oval.

[ ] Yes
[ ] No
[ ] Maybe
[ ] Other: _______________________________

This content is neither created nor endorsed by Google.

Google Forms
A.3 User Study Administration Guide
User Study Administration Guide:

1. Introduction: 10 Minutes (Recording)

- Introduce general information about study

  Welcome participant to study and request completion of Consent Form.

  **Script:**
  This study will be evaluating different methods and educational practices for machining instruction. This study will be conducting several trainings that are focused on the set up procedures for CNC machining. We aim to evaluate the differences and effectiveness of each method.

- Flow of Study

  - Training (VR+think-aloud)
    Groups
    1. VR
    2. Work Instructions
    3. Work Instructions with Error Management
  - UX Survey
  - Assessment Task

  **Script:**
  Today's study will be conducted in two main parts, the first part will be the training portion of the study. During the training portion of the study, the participants will be provided with instructions and learning content in order to complete the machining set up task.

  Following the training, which should take approximately 30 minutes to complete, you will be asked to complete a series of survey questions about the training experience.
After the training and survey have been completed, we will take a brief break. For participants selected to complete a VR training, if at any point during the training you would like to take a break or feel motion sickness, you are free to do so and please inform the facilitator.

After the break, you will be asked to complete the machining set up task that you have just been trained on. This task will be completed using the physical hardware and a machine. Do NOT at any point turn the machine on during the task assessment. Please remember, this study is an evaluation of the TRAINING and not YOU. With that understanding, please complete the task to the best of your ability and maintain a safe pace for the duration of the task.

If you have any questions or need additional information/assistance- the facilitator can provide guidance if you are stuck, but do your best to complete the task with as little assistance as possible.

2. Training: *Limited to 45 minutes*

Video Training: Applies to Both the EM and Procedural Instruction

**Script:**

You have been selected for the video work instruction training. Please review all of the instructions and complete the practice questions. This study aims to…. The study procedure… This study is not aimed at examining your capability, please try your best but no pressure under any circumstances. If you have any questions or need clarification about what is included in the work instructions and practice questions, you are able to ask the facilitator for more information.

The training and content have been organized for a sequential completion therefore it is best to review and complete the page before moving on to the next section.
VR Training:

VR Training Flow

1. Procedural Training
   a. Fixturing Selection Guide
   b. Work Offset Training
   c. Tool Length Offset Training

Order of the Error Management

2. Error Management Instruction Section
   a. Review all 9 types of errors
      i. WCS
         1. Wrong Corner
         2. Wrong Z
         3. Wrong Orientation
      ii. Tool Length Offset
         1. Wrong Tool
         2. Wrong Data
         3. Incorrect Measurement
      iii. Fixturing
         1. Collision
         2. Clamping
         3. Parallelism

3. Practice Section
   a. WCS Practice
      i. Corner Selection
      ii. Edge for Touchoff Selection
      Complete 3 times correctly
   b. Error Identification Practice
      i. Participant Identifies 3 error cases correctly
      1. Or completes all 9 identification

Once the practice session has been completed, the user is free to explore.

Script:
You have been selected for the VR machining training. The training will be conducted in a fully immersive environment and you can walk and use controllers to interact with the scene. If at any point you feel uncomfortable or motion sick, please inform the facilitator and then remove the headset. The removal of the headset may be somewhat disoriented.

During this portion of the training, please verbalize your thoughts as you navigate the learning process. We ask that you think out loud to allow us to better understand your experience as you use the VR training system.

---

**Think Aloud Practice**

I’m going to show you how to think-aloud during the task, so basically, the think-aloud process is we would like you to share your thoughts with us during the study, that means we need you to speak out your mind, your actions, your ideas, your observation, your suggestion and everything that comes up in your mind during the time. Please remember to speak out what you are thinking and doing.

Here is a Think-Aloud Practice for you, please remember speak out your mind:

If you are planning to buy a new iPhone for your daughter’s upcoming birthday, what would you do?

Please talk aloud everything that comes into your mind.

---

The VR training will cover

The training will be completed in the following order:

For the training, you will follow the procedural instructions for the task first.

The procedural instructions are completed in 3 sections:

- Fixture Selection Training
- Work Coordinate Alignment Procedures
- Tool Length Offset Procedures

Following your review of the procedural instruction you will move on to the error and mistake portion of the training. The error management portion of the training will include information and visualizations of 9 common types of mistakes made during the setup process. You can review these errors in any order.
After you have completed the instructional training and mistakes and error portion of the VR training, you will advance on to the practice portion of the training.

There are two practice modes, the first will practice your coordinate alignment and tool touch off knowledge. Secondly, the mistakes and errors practice will ask you to identify any errors you see present in a completed set up.

**Facilitator:**
1. Record the first person VR view
2. Record a 3rd person camera view of the participant with audio.

3. Evaluation: *30 min limit*

**Required Items:**
Prepare the following materials for the study:

- Machine Task Setup Sheet Packet
- Milling Machine
- Assorted End Mills
- Clamping Blocks
- Vice
- Paper
- Tool Length Setter Touch Off
- Edge Finder
- Assorted Stock Material

**Script:**

We will now proceed with the task demonstration portion of the study. For this task, you will be asked to complete a full machining setup for a sample part. All of the necessary equipment and information will be provided. Please note, not all items will need to be used. It is up to your discretion to make the evaluation what items are needed to successfully complete the task and what are not. If you are stuck on the set up, the facilitator can provide you with assistance; however, do your best to complete the task with minimal assistance.

**Facilitator:**
Record the user completing the set up from a 3rd person view.
4. Interview

Provide the user the post-study evaluation. Following the post-study evaluation, proceed with the open question interview.

- **VR**
  - **What challenges did you encounter during the tasks?**
    - How does this challenge affect your learning procedure?
    - What benefits did you see for the VR machining process?
  - Which part of VR training helped you the most in the hands-on evaluation?
  - Which part of VR training do you feel confused or need further explanation?
  - Do you have any difficulties with interacting through the joysticks in 3D space? If yes, please explain in detail.
  - What part of evaluation do you think is uncovered by the VR training environment?
    - What other information about setting up a CNC machine do you want to know but not covered in the training process?
    - And why?
  - Are you satisfied with your overall performance? Why or why not?
  - Do you have any challenges during the evaluation process? If yes, why?
  - If you have previous experience with CNC machining, how does the current strategy differ from your previous experience?

  - How does the error management instruction help you with the set-up process?
  - Compared with traditional machining,
  - Any suggestions for us to improve the system?
A.4 User Study Set Up Task Sheet
Machine Set Up Task
Set Up Sheet

Task Description

Following the training session, you will complete the following CNC milling machine set up task given the provided information. The following items are provided in order to complete the task but not all are required. Using the information provided and the knowledge you have acquired through the training.

Do **NOT TURN on the MACHINE SPINDLE** at any point in the evaluation. If there are steps that you believe require the machine to be on, request assistance from the facilitator. These portions of the tasks will be evaluated without any power to the machine.

**Information Included:**
- CAD Model
- CAM Set Up Information
- Tool for Operation

**Materials Provided:**
- Milling Machine
- End Mills
- Clamping Blocks
- Vice
- Paper
- Tool Touch Off Setter
- Edge Finder
- Measurement Devices
**Task:** Complete the setup of the CNC milling machine given the material & tool information, the toolpath visualization and CAM program that identifies the work coordinate system. All tools, materials and information are contained on the table or in the Machine Set Up Task packet.

**Stock Preparation**

<table>
<thead>
<tr>
<th>Material</th>
<th>Size</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminum</td>
<td>4.2” x 3.5” x 3.25”</td>
<td>N/A</td>
</tr>
</tbody>
</table>

**CAD Model**
**Task:** Complete the setup of the CNC milling machine given the material & tool information, the toolpath visualization and CAM program that identifies the work coordinate system. All tools, materials and information are contained on the table or in the Machine Set Up Task packet.

**Set Up Information & Orientation**

Machine Tool Path Indicated with Blue lines
Task: Complete the setup of the CNC milling machine given the material & tool information, the toolpath visualization and CAM program that identifies the work coordinate system. All tools, materials and information are contained on the table or in the Machine Set Up Task packet.

Tool Information

<table>
<thead>
<tr>
<th>Tool</th>
<th>Diameter</th>
<th>Flutes</th>
<th>Length Offset</th>
<th>Shank Diameter</th>
</tr>
</thead>
<tbody>
<tr>
<td>¼” Endmill</td>
<td>.25”</td>
<td>4</td>
<td>2”</td>
<td>.25</td>
</tr>
</tbody>
</table>
A.5 VR Introduction Document
CNC Training Preview & VR Operation

Choose Training Mode

Instructions  Errors  Practice

Procedural Instructions

Fixturing  Tool Offset  Alignment
Practice & Play
Choose A Mode

- WCS Alignment
- Errors
A.6 Evaluation Sheet
## Task Evaluation Sheet

### Process Checklist:

<table>
<thead>
<tr>
<th>Step Order</th>
<th>Process</th>
<th>Question</th>
<th>Deviated</th>
<th>Corrected</th>
<th>Missed</th>
<th>FP Correct</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fixturing</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>Select the fixture best for the material. (Vice)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Clean vice of any metal chips.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Secure material in fixture</td>
<td></td>
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<td>Slowly lower onto setter/paper</td>
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<td>19</td>
<td>Once at known value, set to Z height</td>
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A.7 Post-Study Questionnaire
**Post-Study Questionnaire**

Thank you for participating in our study. Please answer questions below based on your experience in the task.

* Required

1. **Your Participant ID**

2. **How would you describe your level of experience and familiarity with Computer Numerical Controlled (CNC) machines?**
   
   1: Extremely poor (No experience at all) 2: Bad (Used few times before but not familiar) 3: Average (Occasionally use the system) 4: Good (Interact with the system well and use frequently) 5: Excellent (Expert in the system with a certain level of design/programming background)

   **Mark only one oval.**

   | 1 | 2 | 3 | 4 | 5 | Excellent |

3. **Mental Demand: How mentally demanding was the task?**
   
   e.g. thinking, deciding, calculating, remembering, looking, searching etc.

   **Mark only one oval.**

   | Very Low | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | Very High |

4. **Physical demand: How physically demanding was the task?**
   
   e.g. pushing, pulling, turning, controlling, activating, etc.

   **Mark only one oval.**

   | Very Low | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | Very High |

5. **Temporal demand: How hurried or rushed was the pace of the task?**
   
   The time pressure you feel due to the rate or pace

   **Mark only one oval.**

   | Very Low | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | Very High |

6. **Effort: How hard did you have to work (mentally and physically) to accomplish your level of performance?**

   **Mark only one oval.**

   1- highly satisfied 10- low satisfied

   | Good | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | Poor |

7. **Performance: How successful were you in accomplishing what you were asked to do?**

   **Mark only one oval.**

   Please rate how much do you agree with this statement: "I feel it's intuitive to learn the machine set-up through the proposed learning strategy.”

   | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |

   | Strongly disagree | Strongly agree |

8. **Frustration: How insecure, discouraged, irritated, stressed, and annoyed were you?**

   **Mark only one oval.**

   | Very Low | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | Very High |

9. **Please rate how much do you agree with this statement: "I feel it's intuitive to learn the machine set-up through the proposed learning strategy.”**

   | 1 | 2 | 3 | 4 | 5 | Strongly disagree | Strongly agree |

10. **Please rate how much do you agree with this statement: "I feel the instruction content in the proposed learning strategy was very clear to understand”**

    | 1 | 2 | 3 | 4 | 5 | Strongly disagree | Strongly agree |

11. **Please rate how much do you agree with this statement: "I fully engaged in the instruction content through the proposed learning strategy”**

    | 1 | 2 | 3 | 4 | 5 | Strongly disagree | Strongly agree |

12. **Please rate how much do you agree with this statement: "I feel confident with working on coordinate system alignment (x,y,z axis offset) after receiving training,”**

    | 1 | 2 | 3 | 4 | 5 | Strongly disagree | Strongly agree |

**User experience of learning strategy**

Please tell us about your perceived cognitive workload of perform CNC machine evaluation through the training strategy. For each question, please select the option that is most applicable to you.

13. **Please rate how much do you agree with this statement: "I feel confident with fixtureing selection after receiving training”**

    | 1 | 2 | 3 | 4 | 5 | Strongly disagree | Strongly agree |

**Thank you for your participation!**
14. Please rate how much do you agree with this statement: “I feel confident with tool setting after I received training.”
1: Strongly disagree 2: Disagree 3: Neutral 4: Agree 5: Strongly agree
Mark only one oval.

15. Please rate how much do you agree with this statement: “I can easily notice the potential errors while setting up the machine.” e.g. wrong orientation, wrong tools
1: Strongly disagree 2: Disagree 3: Neutral 4: Agree 5: Strongly agree
Mark only one oval.

16. Please rate how much do you agree with this statement: “I felt easily distracted and it was easy to get lost through the proposed learning strategy.”
1: Strongly disagree 2: Disagree 3: Neutral 4: Agree 5: Strongly agree
Mark only one oval.

17. Please rate how much do you agree with this statement: “I feel the proposed strategy is helpful for CNC machine set-up.”
1: Strongly disagree 2: Disagree 3: Neutral 4: Agree 5: Strongly agree
Mark only one oval.

18. Please rate how much do you agree with this statement: “I feel the need for asking questions from an in-person tutor while manipulating the CNC machine.”
1: Strongly disagree 2: Disagree 3: Neutral 4: Agree 5: Strongly agree
Mark only one oval.

19. Please rate how much do you agree with this statement: “I have strong safety concerns while manipulating the CNC machines.”
1: Strongly disagree 2: Disagree 3: Neutral 4: Agree 5: Strongly agree
Mark only one oval.

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Appendix B

Additional Data
### APPENDIX B. ADDITIONAL DATA

#### Figure B.1: Participant Raw NASA TLX Scores

<table>
<thead>
<tr>
<th>Groups</th>
<th>Mental Demand: How mentally demanding was the task?</th>
<th>Physical demand: How physically demanding was the task?</th>
<th>Temporal demand: How hurried or rushed was the pace of the task?</th>
<th>Effort: How hard did you have to work (mentally and physically) to accomplish your level of performance?</th>
<th>Performance: How successful were you in accomplishing what you were asked to do?</th>
<th>Frustration: How insecure, discouraged, irritated, stressed, and annoyed were you?</th>
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### APPENDIX B. ADDITIONAL DATA

#### Figure B.2: Participant Raw Subjective Experience Scores

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*Table of Participant Raw Subjective Experience Scores across different groups and conditions.*