Proceedings of the ASME 2022 17th International
Manufacturing Science and Engineering Conference
MSEC2022
June 27-July 01, 2022, West Lafayette, Indiana, USA

MSEC2022-xxxx

IMMERSIVE VIRTUAL REALITY TRAINING WITH ERROR MANAGEMENT FOR CNC MILLING SET-UP

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ABSTRACT

In order to address the demand for skilled machinists and limitations with current training programs, we introduce an immersive Virtual Reality (VR) CNC machining training environment for CNC machine setup processes with a novel error management based training curriculum. Current machinist training programs are several years long requiring active mentorship from a skilled individual and are very costly due to the materials and tools required. Mistakes and errors made during the set up process can create safety risks, waste material and break equipment requiring additional time to reset. Existing VR CNC milling training environments fail to address mistakes that can occur during the setup process. In order to address these operational challenges, a novel error-management based training in VR is proposed which allows trainees to learn the set up procedure,learn the common errors & mistakes and practice identifying errors in addition to practicing activities for the setup. The training first introduces students to the setup procedure, followed by demonstrations of error cases and identification and management strategies culminating in practice opportunities. Trainees witness a spatial demonstration of the procedure, guided by auditory and text instructions. Users are able to actively explore the spatial teaching environment while controlling a virtual CNC milling machine. A preliminary user training test is performed comparing the VR method to a video training and a video training with error management curriculum.

1 Introduction

Computer Numerical Controlled (CNC) Machining is an essential and fundamental process supporting the greater global manufacturing ecosystem and supply chain. CNC machining requires advanced training and a skilled workforce to process a design to be dimensionally accurate. The skill gap continues to expand as a result of continued industrial growth and an aging workforce, with large populations retiring in the next 5-10

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years [1]. Current training on CNC milling machines presents several challenges, such as the high cost and safety concerns, which motivates researchers to explore another effective and efficient training strategy. Furthermore, physical CNC training necessitates high operational costs due to the consumption of materials, tooling, and the need for precision measurement devices. Access to CNC milling machines is often limited in educational environments due to the high cost ranging from $15,000 to $100,000 [2]. High operating costs and expensive machinery limit the availability of CNC milling machines dedicated to training inexperienced novices.

Traditionally, CNC training is taught by an experienced machinist with extensive knowledge of machine controls and behavior. The requirement for highly skilled instructors creates an added strain on the limited supply of skilled machinists in the workforce. The training exposes novices to unfamiliar industrial equipment with inherent safety risks [3]. The spinning cutting tools and metal debris can harm an operator during operation. Improper mounting of tools and material can lead to rapid destruction of material, tools and machinery and potentially harm the operator. CNC milling machines operate under computer control and machine operation can be perceived as unexpected. The complexity of understanding CNC programs combined with the safety risks of operating industrial milling machines creates significant safety risks for novice trainees with limited experience.

Manual involvement is largest during the programming phase, converting the model into machine toolpaths, and during the machine set up process. The machine setup process prepares the machine and material for cutting as defined by the programmed control. Human errors and mistakes with machine set up processes, such as coordinate misalignment and tool setting errors, can increase costs because of unusable material that does not meet customers' specifications and with potential damage that can be incurred. The setup process is error-prone because novice machinists perform complex mental spatial transformation of the work piece to align to the machine. These spatial transformations create high cognitive load and training around the resultant errors is important to reduce negative effects [4]. Errors during the setup process can result in broken tools, fixtures and damage to the machine. Mistakes are an inevitable reality of human operation and learning. Error management training has been found highly effective in environments with a high cost of errors where safety is imperative, such as in surgery [5] and pilot training [6]. Error management training has shown efficacy in reducing errors during operation and increasing trainee confidence during a task [7].

The capability of Virtual Reality (VR) to create a seamless and immersive environment brings great opportunities in the education and occupational training field. With the anticipated growth of Head-mounted displays (HMD), VR provides a means to access virtual training workspaces remotely and address the safety and cost concerns [8]. What's more, previous researchers have developed the training workspace by integrating the realistic 3D simulation of milling machines [9–11]. Nevertheless, none of these existing works pay attention to error management in machining training. It is still an open question if VR can be used to support the CNC machining training space with error management and address the limitations of traditional training strategies. Our research question is *how can CNC machining training be improved for novice trainees to have hands-on experience while learning set-up procedures theoretically with an awareness of error management*.

In order to equip trainees with procedural knowledge and a framework for identifying, verifying and mitigating potential mistakes made during the setup process, we present a VR-based CNC training system with error management instruction. We aim to address the challenges previously discussed. Restrictions on limited availability of expert machinists available for training is alleviated with the systematized VR curriculum. Furthermore, harm from cutting tools and material debris are eliminated in a virtual environment. Students are able to familiarize themselves with machine operation, control and procedural knowledge prior to exposing themselves to a real machine [10]. The virtualization of material, machines and tools reduces the cost of training significantly [12]. Limited machine access for training is alleviated through the creation of an immersive life-like machining environment in the virtual training environment. This paper applies the established error management training philosophy which includes error identification methods, discussion of error impacts and lastly potential mitigation strategies, to CNC milling machine training in a VR environment.

We make the following contributions in this work:

1. A well-structured CNC milling machine setup training method based on a novel error management approach including coordinate system, fixture selection and tool set-up
2. A VR-based CNC machining training system that provide users with auditory and visual feedback on a virtual representation of a CNC milling machine.

2 Related Works

Our work is motivated by previous research related to the background and we explore the current state machining training programs and current developments. Next, we explain in detail about prior work utilizing error management training theory. In the end, we present a series of previous work related to VR/AR machining training systems.

2.1 Machining Training

Current machinist training occurs primarily in apprenticeship programs and community college certification programs [13]. These programs share hands-on experience as a primary component of the training process; however, community college programs include more time in a traditional formal instruction environment [14]. Curriculum & standards for apprenticeships in the U.S are defined by state vocational training program requirements [15]. 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 [16]. Researchers have begun to integrate cognitive science and educational research practice to improve the CNC machine training experience and long term efficacy by performing cognitive task analysis to inform VR training for the tool length offsetting process. Nathanael et. al demonstrated that training can be accomplished in VR for a training that traditionally requires sensory-motor feedback if the training elements are carefully designed with cognitive considerations [17]. In spite of these advancement, current machining training still suffer from the high cost, low efficiency, and potential safety issues.

2.2 Error Management Training

Other educational practices 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 [7]. The error management strategy has been found to improve the transfer of learning in simulation-based training [18]. Error management training has been largely investigated in literature for use cases where mistakes and errors can have detrimental effects such as surgery [19] and pilot training [20]. 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. The error management training in simulated surgery environments was shown to improve confidence and reduce errors made during the evaluation; however, it is unknown how to apply error management training strategy into the CNC machining instruction [21].

2.3 VR Training System

VR environment training for machining has demonstrated the benefit of reducing the harm caused and requirement for repair [22]. The CNC Partner implemented a semi-immersive training environment paired with a physical interface that recreated the machining workflow and CNC functionality ranging from part setup, measurement taking, manual data entry, NC programming, cycle execution and processing [12]. Yang et al. proposed a training system that allows the user to interact with the virtualized objects in a real environment (AR) with their hands in a natural interface and demonstrates a reduction of failures during operation and fewer inquiries during the setup phase in comparison to video training [23]. In order to evaluate the effectiveness of the training design, Chen et al. evaluated approaches to the design of the instructional content for machine tool operation and found context based instruction more effective than sequential instruction [10]. Other work has evaluated operational support with an AR system integrating additional process information to provide operators guidance and control information instead of training content [24]. Mill Instructor proposes the simulation of a realistic CNC milling machine for safe practice of CNC operations. VR Researchers have demonstrated the ability to simulate all functionalities of machine operation and over time the immersion has become more spatial and achieved higher degrees of realism [25, 26]. These prior works demonstrate the benefits of VR training for machining, with the virtual replication of the real machines, that allow for safe and low-cost exposure to CNC milling machines. However, the content of the training does not address the mistakes that a human operator can make which can result in significant consequences.

3 Training System Design

Our training is designed from the perspective of reducing trainees' cognitive load. Since the machining training is a complex process, it brings high cognitive load to the trainees, especially novices. Based on the Sweller's Cognitive Load Theory (CLT) [27], CLT refers to the amount of load generated when specific tasks are added to the individual's cognitive system. More specially, there are three types of cognitive load, including intrinsic cognitive load, extraneous cognitive load, and germane cognitive load. Intrinsic cognitive load is the load associated with the specific learning contents, which is the inherent difficulty of the learning objects [28]. The extraneous cognitive load on the other hand describes the load generated by the ways and methods which are presented in information or tasks [29]. Germane cognitive load refers to the work put into creating a permanent store of knowledge, or a schema, it is the elements that aid information processing and contribute to the development of "schemas" [29]. Effective instructional system design can help to handle the intrinsic and extraneous load, therefore increasing germane load [30]. Researchers have come up with principles of designing instructional curriculum for health professional training [31]. Inspired by their idea, we also propose several guidelines to design our training system, including: 1) visualization of the spatial transformation of objects to manage the intrinsic cognitive load; 2) procedure instruction and error management instruction to reduce the extraneous cognitive load, and 3) repetitive practice on error management to increase Germane cognitive load.

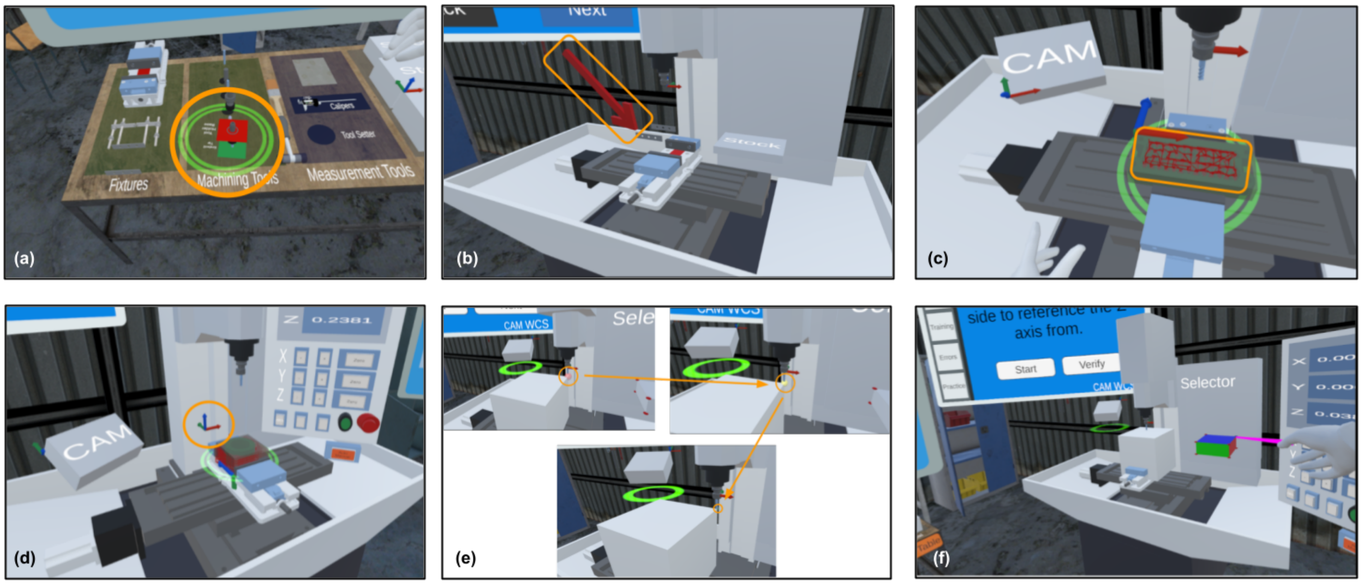

FIGURE 1. Spatial Indicators and Interactions: (a) region of interest, (b) attention pointer, (c) toolpath visualization, (d) virtual W.C.S,(e) origin placement feedback, (f) corner selection practice.

3.1 Machine Interface

The CNC milling machine can be controlled through a virtual Human Machine Interface (HMI) shown in Fig.2. The virtual HMI includes a positional digital read out of the tool location, and positional control for the X,Y and Z axis. Furthermore, the machining set up process necessitates control fidelity and the HMI includes the ability to set the Zero position for the corresponding axis. Additionally, granular increments for control allow for the user to select a desired positional adjustment increment similar to coarse and fine modes on many machines. The increments for control range from .001" to .1" and all intermediary order of magnitude increments.

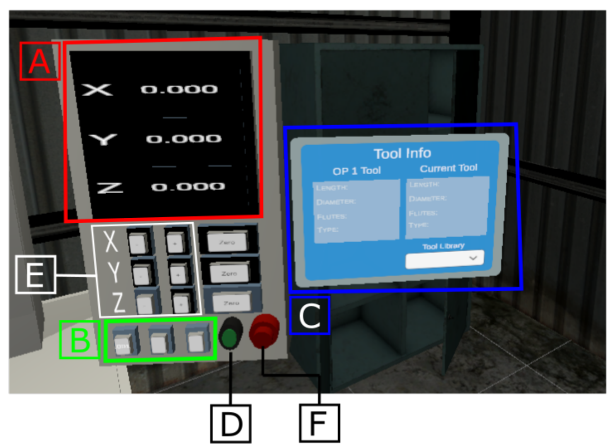

FIGURE 2. Virtual Human Machine Interface (HMI) including (a) positional readout, (b) jogging granularity selection from .001" to .1" in, (c) virtual tool library information, (d) spindle power, (e) axis jogging control and a (e) emergency stop.

3.2 Machine Operation

The following operational interactions have been implemented into the machine control:

Positional Control: Move the machine table in the X,Y axis and spindle height in the Z direction. Jogging the machine can be done incrementally for coarse and fine control. *Set Zero Position*: Coordinate origins can be established by setting axis origins. Users can position the machine and tool into desired location and set the zero position for each axis. *Turn Spindle On/Off*: The machine spindle can be toggled on and off to simulate actual rotation of a cutting tool.

3.3 VR Environment

In order to support the training content, several mechanisms for visualization have been developed. These components serve as visual aids to help 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 into attention guidance and training interaction support.

Focus Region: Highlights regions where actions upcoming actions will be occurring, as shown in Fig.1 (a).

Point of Interest: Indicates a specific component or location on component that is of importance to the instructional content [32]. See Fig.1 (b)

Viewing Zone: The viewing zone is the ideal viewing location to watch the demonstration process.

Virtual reality offers the benefit to place virtual indicators in a 3D environment. Several virtual indicators have been implemented during the training to reinforce spatial concepts that can not be visualize in a traditional training.

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 a computer program in a computer aided manufacturing software. The system is 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 in Fig.1 (c).

Virtual Work Coordinate System: The active work coordinate system is rendered with an origin triad to visualize changes during the WCS setting process. This overlay is intended to reduce instructional confusion very common in traditional training (See Fig.1 (d)).

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.

Additionally, the system design includes spatial visualizations and interactions to support the practice of the procedural tasks. Two practice activities were implemented for the work coordinate system alignment task. User's are presented with a virtual arrangement from a CNC program and have to accurately select the sides to establish X, Y , Z axis on in addition to selecting the correct corner. The following interaction components have been designed supporting the procedure:

Origin Placement Feedback: Users are provided visual feedback on the accuracy of their selected position. The magnitude of the error is represented by colored regions of validity (Shown in Fig.1 (e)).

Work Coordinate System Selection Practice: Trainees can practice matching the origin location from the CAM program and onto the virtual stock material by selecting the appropriate corner. The practice also includes selecting faces of the stock material to touch off to establish X, Y, Z zero positions as seen in Fig.1 (f).

3.4 Procedural Training

The training is composed of procedural instruction training as a primary base for the curriculum. Robust understanding of the process for machine set up is required to perform the task successfully. A multi-modal instructional approach was implemented to support a wide variety of learning preferences. During the procedural instructional experience, spatial animations in the immersive environment occur that map directly to the actions required for manipulation by the student during the setup process. In addition to the spatial demonstration, text instruction is provided in conjunction to auditory instructions. The textual and auditory instructions are synchronized with the spatial demonstration and can be reviewed and revisited by the student. Trainees of the system choose the pace of the instruction as they navigate through the procedure. The procedural instruction is broken down into the 3 sub tasks for the machining set-up process as follows: 1) Selecting a fixture for material; 2) Establishing & aligning the work coordinate system; 3) Tool Setting and Length Offsetting

4 Error Management Training Module

4.1 Workflow

The workflow of the error management training module is presented in Fig.3, and consists of the follow main steps: 1) Introduction of Common Errors, 2) Error identification practice, and 3) Review of the identification performance. The error management module is supported by multi-modal instruction and a spatial representations of all the error modes. Users are able to explore the environment during this phase of the module to understand how the error can manifest.

4.2 Introduction of Common Errors

The error management instruction is integrated into the same framework as the procedural instruction following a similar multi-modal instructional design including spatial demonstrations, and textual and audio guidance. The interfaces across each training module are continuous & identical to reduce confusion for the user and to focus on the error management content. The error management content has been developed in consultation with expert machinists, and machining instructor input on the most prevalent error cases and mistakes made by beginner student machinists. From expert input, the error cases were classified into set-up phase based mistakes, and the three error types are as follows (shown in Fig.4):

Work Coordinate System Errors: The work coordinate system errors of interest implemented in the training are incorrect orientation, incorrect origin corner and Z zero plane selection error. An "Incorrect Orientation" error is discontinuity of the established work coordinate system and how the stock material is orientated in the fixture with respect to the coordinate system defined in the CNC program generation process. An "Incorrect Origin Corner" error is a deviation from the corner or feature used to locate the Work Coordinate System in the computer aided manufacturing CNC program process. For example, a program may define the top right corner of a piece of stock material as the W.C.S and a machinist may locate the coordinate system origin

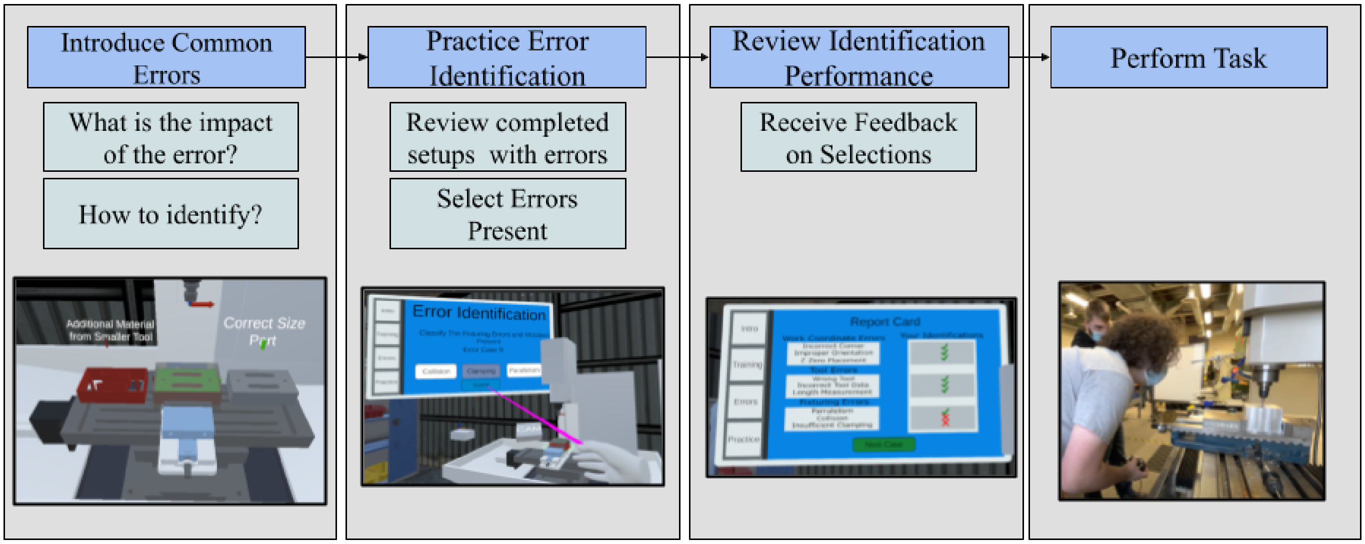

FIGURE 3. Error Management Practice Flow

on the top left corner and this would constitute as a "Incorrect Corner" error. This error can be made in conjunction with an incorrect orientation error or independently if the stock is placed correctly. The final WCS error is the Z plane error. This error occurs when the CAM program defines either the top or bottom of the stock material as the Z Zero plane and the machinist selects the opposite for the Z Zero plane.

Tool Setup Errors: The tool setup errors integrated into the error management curriculum are "Wrong Tool", "Incorrect Tool Information", and "Tool Length Measurement Error". A wrong tool error occurs when the intended tool in the CNC program is different from the tool in the milling machine. An "Incorrect Tool Information" error occurs when the information defined in either the machine tool database or CAM program are discrepant. This can occur when modifications are made and not updated, later impacting other tool changes. The final tool setup error is the "Measurement Error" and this error occurs during the measurement of the tool length offset. The "Incorrect Tool Information", and "Tool Length Measurement Error" manifest similarly and are treated as equivalent for error identification however the nature of the error is different.

Fixturing Errors: The three fixturing errors are "insufficient clamping", "collision error", and "parallelism error". An insufficient clamping force error occurs when the fixture is not capable of securing the stock material against the cutting forces of the endmill and the material shifts out of position. A collision error occurs when the fixture interferes with the toolpath and causes a crash or collision. A parallelism error occurs when the stock material placed into the fixture is not parallel to the machine table and no accommodations are made to account for the angle.

The error cases for the Error management curriculum were refined to only include the top 3 errors or mistakes that occur at a high frequency and have a significant impact on the success of the machining operation.

4.3 Practice of Error Identification and Review Performance

Literature in the education and training domain has demonstrated the improved efficacy of an error management strategy when paired and reinforced with a practice phase before full execution of the task [33]. A structured practice environment has been implemented to reinforce retention of the error & mistakes instruction as well as the procedural knowledge. Error Identification practice presents a machine set up with an unknown error present. The user is tasked with evaluating the set up and classifying the error present. The trainee practices identifying multiple different error cases with a simulated complete setup. Each setup has unique errors modeled for identification practice and feedback is provided on their selections. A "Report Card" is generated indicating whether or not the trainee successfully identified the presence of an error.

5 Implementation

The immersive training environment was developed utilizing Unity3D. Unity3D is a 2D/3D platform for building scenes, processing user input and managing digital CAD and design assets. Unity3D [34] is responsible for rendering the 3D environment to VR headsets. This work utilized an Oculus Quest HMD for display. The machine simulated is a Tormach 1100 [2]. The VR CNC milling machine is established using high fidelity mechanical CAD files and removing internal components which do

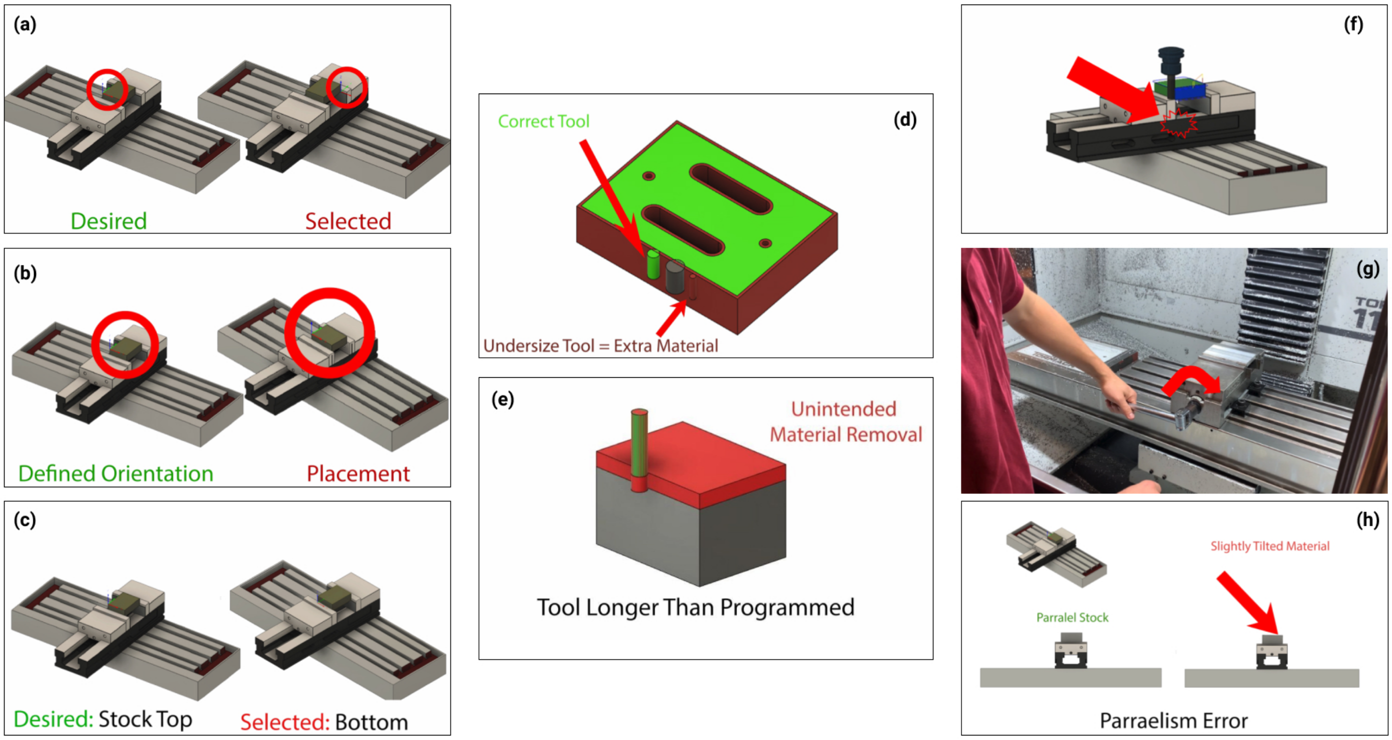

FIGURE 4. Screenshots of different common errors presented in Traditional video-based Error Management Training: *(From left to right)* The first column represents Work Coordinate System Errors: (a) Wrong corner, (b) Wrong orientation, (c) Wrong Z. The second column represents Tool Setup Errors: (d) Wrong tool, (e) Wrong length. The third column represents Fixturing Errors: (f) Collision, (g) Clamping, (h) Parallelism

not alter the fidelity. From this refinement, motion control groups and relationships are created to allow for a realistic operation within the constraints of the real machine. While the simulated machine is created to a high degree of fidelity and realism with similar mechanical constraints such as machine travel extents, the entire training system has been designed to train students regardless of machine they may use. Elements of realism such as machine travel speed are not imperative to model to a 1:1 realism however care is taken to model all elements within reason of comparable operation.

6 Preliminary use case

We conducted a preliminary use case study to test the prototype of VR CNC machining training system based on error management. We tested three CNC training methods with three participants individually, namely *traditional procedural training*, *traditional procedural training with error management*, and *VR training*.

6.1 Study Setup

Before the study, participants reported they never received CNC machining training before. After receiving training, participants were asked to complete a physical machine set-up task by following a task script. We turned the spindle off for safety concerns. The set-up procedure contains several sub-tasks, which are fixture selection, measuring tool length, coordinate X axis and Y axis, and zero Z axis. Meanwhile, their performances were recorded to verify the effectiveness of the training systems, such as performing time (seconds) and performance error. Later, they provided some subjective feedback through a post-study questionnaire and debriefing session. The Nasa-TLX [35] questionnaire was used for measuring the cognition load.

Through the VR training system, the participant was equipped with a H.M.D to render the virtual scene in an controlled in-lab environment. Before the formative training, researchers demonstrated the representation of 3D simulation such as the milling machine and the operation of joysticks to eliminate the learning curve from VR devices. The participant is loaded into a virtual machine shop which contains a CNC milling machine, a tool table with a variety of machine tools and a virtual instruction panel. In the VR training, the participant received procedural training, nine types of common errors, and practice sessions by sequence. The comparison training video was filmed by researchers to make sure the training content is consistent with the VR training. Every training session was controlled within 30 minutes.

6.2 Preliminary Result

Through the comparison on Nasa-TLX [35], on the scale of 1-10, we found that the cognitive load of the participant on traditional procedural training with error management (Mean=2.83) is the lowest than the other two conditions, which are traditional procedural training (Mean=3.67) and VR training (Mean=5.67). We suspect that the unfamiliarity of VR environment and interaction could be the cause of the higher cognitive load, and expect to conduct a more comprehensive user study in the future to figure out the reason. On the other hand, the participant trained in the VR session (1478s) completed the task evaluation faster than two traditional methods, traditional procedural training (2259s) and traditional procedural training with error management (1874s). In addition, the participant of the VR training identified the **Incorrect Origin Corner** happened in the evaluation. She further elaborated on how error management instruction affects her evaluation performance. This participant reflected on her error retrieve process that she inferred the error happened when the result was not matching with her initial goal. As she mentioned: *"The error management helped me notice what I was doing wrong with that. Because when I was talking about, if you have chosen an incorrect spot, like those are the areas that you're going to get. And I noticed immediately because of the management wonders, here's different ways you can mess up."*

7 Conclusion and Discussion

The CNC set up error management training allows trainees to follow spatial instructions and visualizations in virtual reality and practice identifying such errors. Through the use case evaluation, users expressed support and found that the error management training increased confidence when they felt uncertain through the task evaluation. This qualitative feedback and preliminary data demonstrate that the error management training approach helps to reduce errors made during set up and helps trainees to think critically to resolve any mistakes made during the setup process.

However, user feedback during the use case suggests improvements to the system for a better user experience and efficacy of the training. During the procedural training, the user was not certain what was the most critical take away or what to focus their attention on. Additional interface guides could help to guide the user through what the expected action is. Opportunity to expand the degree of interactivity during the error management training exists. During the use case task evaluation, the participants asked if they could reference the training session again. In order to increase the efficacy of the training, potential modification of the training structure could yield improved retention and strengthen long term recall of error identification. The current training design exposes trainees to both the procedural instruction followed by the error management session and then task evaluation. An improved training system could consist of Procedural Training, Initial Task Evaluation, Error Management Training, and Task Corrections & Final Task Evaluations.

All participants expressed an excitement and understanding for the VR error management training system suggesting collaborative experiences in a multi-player environment. Future work to allow interaction between trainees and experienced instructors is of interest to evaluate the training efficacy and scalability of the training system.

ACKNOWLEDGMENT

This work has been partially supported by the National Science Foundation (NSF) under Award No.20336157, Grant DGE-1922591, and the Grant Writing Bootcamp Funding 2020 from Rochester Institute of technology.

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