Work-In-Progress Paper: A Generalizable Virtual Reality Training and Intelligent Tutor for Additive Manufacturing

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***Abstract*—There is currently significant demand for training in how to use metals additive manufacturing (AM) machines. Such training is important not only for the technicians who run and maintain the machines, but also for engineers and strategic decision makers who need to support AM part fabrication. Furthermore, there are a variety of AM machines, each with different details to be learned and potential hazards to overcome, and it is difficult to train more than a handful of users at one time. To address these challenges, a prototype training system has been developed, the *AM Training Tutor*, which uses interactive virtual reality (VR) to train users on a specific AM machine – the EOS M290. To make the training technology more widely available and expand its use across a variety of different AM machines, efforts are underway to develop a modularized and generic version of the *AM Training Tutor* that can be customized with relatively little effort to train users to operate other AM machines. This paper details the progress to-date, challenges and proposed solutions with the aim to demonstrate how standalone VR-based training systems can be redesigned for relatively easy repurposing and generalization.**

Keywords—generalized VR, VR-based training, workforce training, cognitive tutor, advanced manufacturing, additive manufacturing, 3D printing

I. Introduction

Additive manufacturing (AM), commonly referred to as 3D printing, is a manufacturing method in which parts are created by adding material – whether polymer, metal, ceramic, or otherwise – in a layer-by-layer fashion.

There is an increasing and acute demand for training students, technicians, operators, and engineers in the operation of AM equipment [1].

The *AM Training Tutor*, an immersive Virtual Reality (VR) experience supported by an underlying intelligent tutor, was developed to address these demands and challenges. It is an interactive instructional system that simulates the operation of the EOS M290 laser powder bed machine, one of the most commonly used AM systems today. Students or trainees interact with the virtual version of the machine and, as they progress in the VR system, receive feedback on whether they are taking correct and reasonable steps in setting up part builds. Users can also request hints as they work with the tool. This type of training is known as "cognitive tutoring" and is supported by the Cognitive Tutor Authoring Tool (CTAT) [2].

This approach has a number of advantages. First, the students who are learning how to safely use the AM machine will not need to directly access the actual hardware or be exposed to hazardous materials. Given the costs and limited availability of AM machines, it is important to have a way to provide students with experience and learning opportunities without the machine being directly available. Second, this approach will allow the inclusion of instructional support that does not require instructors to be available to provide feedback. The interactive software is not intended to replace in-person training on actual AM machines – an invaluable experience – but will allow safe preparation in a virtual environment and reduced training time in front of the machines. The approach will also increase the capacity to teach large numbers of students or trainees.

The first version of the tutor was limited to a specific machine and not designed to provide training for a variety of AM equipment systems. While some of the general skills required for operating the EOS M290 are transferable to other AM machines, operating different systems requires new knowledge and further training.

Thus, current efforts are focused towards transforming the *AM Training Tutor* into a generalized framework that can be applied rapidly and efficiently to other AM equipment models.

II. Related Work

Virtual Reality (VR) has wide applications across academia and industry. It has been successfully utilized to build educational technologies that are driven by Artificial Intelligence (AI) and learning science principles [3]. Its adoption in design and prototyping of manufacturing and machine assembly methods is well-documented [4, 5]. In the healthcare sector, VR plays important roles in medical education and medical procedures such as surgical simulation [6]. VR-based training systems, within the context of manufacturing, are used in sectors ranging from the automotive industry [7] to manufacturing machinery [8] and, in particular, to reduce inherent health and safety risks through virtual training in sectors such as mining and construction [9, 10].

Of particular interest to the work presented here is how VR is used in training engineering students to operate machinery. Researchers have shown how VR can be used to model and simulate interactions with Computer Numerical Control (CNC) machines to supplement instruction in courses involving a large number of students while minimizing the risk involved in operating these machines [11]. Most recently, researchers demonstrated the use of VR to deliver collaborative virtual learning experiences to students ahead of on-site training, supporting the argument that VR can serve as a safer and cost-effective training tool [12].

While the above studies demonstrate the effectiveness of VR in training to operate machinery, their application is limited to specific machines and does not address the issue of how these systems can be repurposed or reconfigured for training on variants or different models of such machines. The DIVERSE framework [13] and ViSTA Widgets [14] may be used to build reconfigurable VR environments and 3D interfaces but both frameworks require having high technical knowledge of their platforms. Moreover, they are not tailored to training systems. Earlier demonstrations of a reconfigurable VR application focused on reducing the complexities of converting and importing 3D models built using Computer Aided Design (CAD) software into the VR application as needed and switching between simulations without recompiling the VR application [15, 16, 17]. Although these studies make substantial contributions in design and engineering approaches to building decoupled and reconfigurable systems, they are limited in a number of ways – they are non-immersive desktop applications, they do not fully demonstrate how to design training systems that maximize reusability of components such as 3D models and, most importantly, they provide prescribed on-screen instructions on how trainees should interact with the simulation instead of a guided tutorial approach with real-time feedback. In other words, there is little evidence that training is informed by learning science principles.

The design and development of VR-based training systems and educational technologies in general should be guided by such principles. Moreover, VR-based training systems for manufacturing equipment should be designed and implemented with the consideration that the development of new models, parts and variants has as little impact as possible on their reusability. No work was found in the literature that takes this critical consideration into account. This work addresses that and presents progress in the development of a generalizable VR-based training framework for one of the fastest-growing manufacturing technologies – Additive Manufacturing (AM).

III. The AM Training Tutor

During the initial implementation of a hands-on AM Laboratory course in 2018, logistical challenges were experienced in teaching 18 students and concerns were raised about the likelihood of increased enrollment in future years. With a practical limit of only a small number of students and an instructor in front of an AM machine at one time, a prototype interactive system that includes both declarative (PC-based) and procedural (VR-based) instruction was developed. The *AM Training Tutor* simulates the operation of the EOS M290 with instructional support for students learning how to use the machine. As part of the 2020 AM Lab course, 27 enrolled students had the opportunity to individually complete the declarative (PC-based) instruction prior to attending in-person lab sessions on the operation of the actual AM machine. In 2021, the AM Lab course students, as well as others seeking instruction on the applicable equipment, will use both the declarative (PC-based) and procedural (VR-based) modules of the *AM Training Tutor* to support their training.

The *AM Training Tutor* guides students in learning the necessary safety procedures, equipment components and operational steps for setting up the EOS M290 for 3D printing. This framework is supported by a VR system that prompts students, step-by-step, to set up the equipment. Students can virtually "grab" machine components and move them from one location to another to install them, load the metal powder used for 3D printing, install and level the build plate, and perform all of the actions needed for actual machine setup. Fig. 1 shows a student operating the EOS M290 AM machine in the VR simulation. The instruction has a high degree of fidelity to actual machine setup and use. Hints are provided, if requested, with feedback typically in the form of highlighting objects on and near the machine for the required steps. A 4-minute video demonstrating the first version of the *AM Training Tutor* is available at https://bit.ly/2M6ICbn.

IV. Transforming the AM Training Tutor to a Generalized Training Framework

While the first version of the *AM Training Tutor* is fully functional, it can be applied to train users only on a specific AM machine. This prototype involved significant development effort by the interdisciplinary team which required a full year to detail instruction, design 3D assets, develop the VR application and create cognitive tutor logic. This implies that creating a tutorial for a different AM machine would require similar effort and resources.

Fig. 1. A student operating the VR-based *AM Training Tutor* for the EOS M290 AM machine

In order to reduce this requirement as much as realistically possible, current efforts are focused on transforming the tutor into a generalized framework with the specific goal of making the VR application versatile enough that it will not require recompiling the application every time tutorials for new AM machines are created.

Although the procedural (VR-based) instruction of the *AM Training Tutor* is implemented as a client-server architecture, all 3D assets and some tutorial logic were implemented in the VR application for the prototype system. This made generalizing the VR application very difficult. After multiple design sessions, a blueprint was created for the new generalized framework and the following major tasks were identified to implement it.

- Migration of all 3D assets from the VR application to a remote asset repository
- Extraction of all 3D asset information and other details specific to an AM machine into a remote configuration file
- Migration of all tutorial logic embedded in the VR application to the remote cognitive tutor (CTAT) service
- Development of a web application to build tutorial configurations for new AM machines

Fig. 2 demonstrates the earlier architecture of the *AM Training Tutor* compared to the new generalized architecture. Backend services and repositories that are hosted via on-site cloud services have been developed.

A. *Current Progress*

Significant progress has been made toward generalizing the *AM Training Tutor*. The system is able to load all tutorial assets from a remote service by consuming configuration information provided by the service. By altering properties provided in the configuration file, modifications can be made to the tutorial without recompiling the VR application. Development of a web application to build tutorial configurations is also in progress.

B. *Challenges*

One of the greatest challenges is reducing the time needed to load 3D assets from a remote location during tutorial startup. Due to the very high resolution of textures of the 3D models, the total download size may exceed 1GB, which may require over 10 minutes to import into the VR application. Ways to balance loading time and 3D texture quality are currently being explored.

The intended audience for the tutorial configuration builder is AM experts with little or no technical background in VR application development. This, however, may be challenging as tutorial configurations must be readily interpretable and usable by the VR application code itself. It is also likely that the configuration builder will require at least limited assistance from a programmer or an expert in VR applications.

And, while every effort is made to reuse 3D assets across AM systems, some properties or textures are specific to individual AM machines. Thus, new artwork will be needed for certain parts of new AM machines. The *AM Training Tutor* will then enable the creation of tutorials for new AM machines by loading all existing and new artwork according to information provided in the tutorial configuration file.

V. Conclusion

By generalizing the *AM Training Tutor*, instructional systems for similar AM equipment can be developed in much less time than was needed to build the initial system. To test the generalization, a new tutorial will be created for the ExOne Innovent located in an on-site AM laboratory and also used by the AM Lab course students. Achieving this milestone will demonstrate how to successfully repurpose and generalize existing training systems and how to make use of cognitive tutoring and established learning science principles to build such systems, contributions that are absent from the current literature. Further, it is anticipated that this project will have a broad impact by contributing to ongoing efforts to address the shortage of skilled technicians and operators of AM equipment. Finally, to fully test and prove the generalized framework developed, iterative testing of the technology with a variety of users including students, AM technicians and engineers, on-campus and in industry, will be done.

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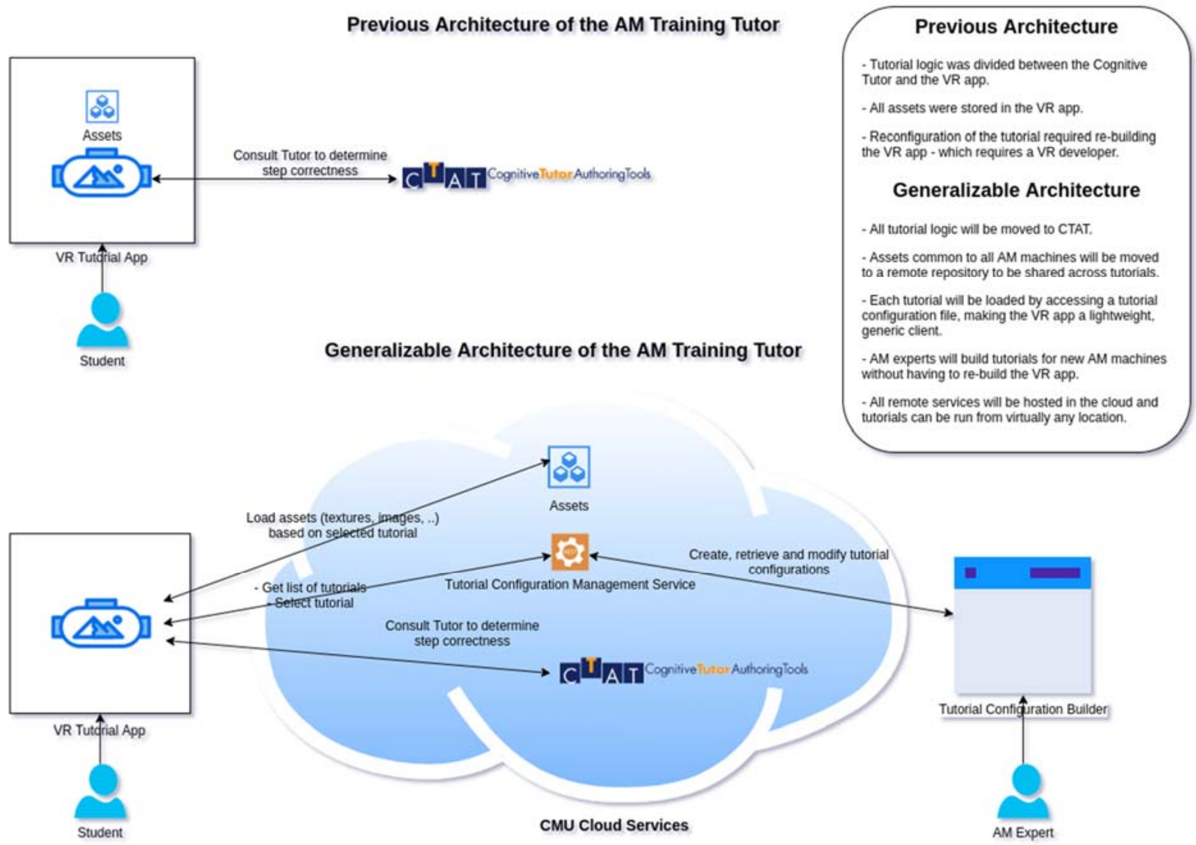

Fig. 2. Comparison of the previous and current *AM Training Tutor* architectures

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