# 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 on each of these machines. To address these challenges, an initial 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, we sought to transform the tutor into a generalized training system that can be customized with relatively little effort to train users to operate other AM machines. To this end, we are currently working on developing a modularized and generic version of the *AM Training Tutor*. In this paper, we present our progress, the challenges we have faced and how we propose to address them. Our aim is 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***

## I. Introduction

Additive manufacturing, 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. As society seeks to move toward cleaner and more sustainable means of production and consumption, additive manufacturing has great potential in supporting this development.

There is an increasing and acute demand for training technicians, operators, and engineers in the operation of AM equipment [1]. In fact, lack of appropriately skilled AM workers has been identified as one of the greatest barriers to wide-spread adoption and implementation of AM. As companies decide to incorporate or outsource AM for prototyping and/or manufacturing of products, the need for appropriately skilled workers is becoming ever more urgent. In addition, training workers in the use of AM equipment is very challenging due to the time and cost of training. There are also hazardous aspects of the AM process that make it difficult to provide trainees with direct and realistic setup and operation experience. Thus, supplemental and off-line instruction are vital to learning the setup and operation of the AM equipment.

As AM spreads across the metals manufacturing industry (from initially being concentrated in aerospace), more and more companies face this issue internally. At Carnegie Mellon University (CMU), we have faced this issue in the past several years when teaching Additive Manufacturing Laboratory courses to a growing number of students (from 18 in 2018 to 27 in 2020).

The *AM Training Tutor*, an immersive Virtual Reality (VR) experience supported by an underlying intelligent tutor, was developed to address these needs and challenges. It is an interactive instructional system that simulates the operation of the EOS M290 laser powder bed equipment, one of the most commonly used AM machines today. Students interact with the virtual version of the machine and, as they take steps in the VR system, they receive feedback on whether they are taking correct and reasonable steps in setting up part builds. Students 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 tutoring approach has been widely successful in training students across a range of domains [3, 4, 5].

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. 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 us to devise instructional support that doesn't require class instructors to be available to provide feedback. Our interactive software will not entirely replace in-person training on actual AM machines, but will allow reduced time in front of the machines. The approach will also increase the capacity to teach large numbers of students or trainees. Though our current efforts are focused on AM, our virtual tutoring approach can be applied to any advanced manufacturing machines that are limited in their availability, with limited human instruction available.

The first version of the tutor was limited. In particular, the tutor was not developed 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 equipment, operating different AM equipment requires new knowledge and further training.

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

## II. The AM Training Tutor

During the first delivery of our AM lab course in 2018, we encountered logistical challenges in teaching 18 enrolled students, with a practical limit of only 3 students and an instructor in front of an AM machine at once. The solution to these challenges required an interdisciplinary effort by researchers from the Human-Computer Interaction Institute (HCII), the NextManufacturing Center (NextM) and the Entertainment Technology Center (ETC) to develop a prototype interactive system that simulates the operation of the EOS M290 with instructional support for students learning how to use the machine. Our team successfully created both PC- and VR-based experiences with cognitive tutoring capability for instruction on the EOS M290 laser powder bed equipment, one of the most commonly used systems in our AM laboratory on campus and in industry today. As part of the course, students first attend in-class lectures, followed by declarative (PC-based) and procedural (VR-based) instructions, after which they operate the actual AM machine during lab sessions.

The declarative instruction of the *AM Training Tutor* helps students learn the required safety procedures and identify the various components of the EOS M290 machine. Students are shown visuals of the equipment and are prompted to identify the important components of the machine. They can request hints if needed and are provided feedback on the correctness of their work, in cognitive tutor fashion, as earlier described. It is web-based and can be accessed by students from their own computers.

The procedural instruction of the *AM Training Tutor* guides students in learning the necessary steps for setting up the EOS M290 for 3D printing. This part of the framework is supported by a virtual reality 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 powder, 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. This part of the instruction has a high degree of fidelity to actual machine setup. Hints are provided, if requested, with feedback, mostly in the form of highlighting objects on and near the machine for the required setup steps. A 4-minute video demonstrating the first version of the *AM Training Tutor* is available at https://www.youtube.com/watch?v=GLcJ1tx1OCw.

## III. 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. The first year of our project involved significant development effort. Nearly 20 person months were spent in designing 3D assets, developing the VR application and creating cognitive tutor logic. This, in general, implies that creating a tutorial for a different AM machine would roughly require expenditure of the same amount of effort and resources. In order to reduce this requirement as much as realistically possible, we are working to transform the tutor into a generalized and highly decoupled framework. In particular, we aim to make the VR application versatile enough that it will not require us to recompile the application every time we create tutorials for new AM machines.

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. This made generalizing the VR application very difficult. After multiple design sessions, we created a blueprint for the new generalized framework and identified the following major tasks 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
- Development of an interface in the VR application to configure the location of remote services
- Development of an interface in the VR application to enable students to choose from a list of available tutorials
- Development of a mechanism to enable the VR application to load all required assets for a specific AM

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

machine based on information provided by the remote configuration file

- Migration of all tutorial logic embedded in the VR application to the remote cognitive tutor (CTAT) service
- Development of web services to manage storage, retrieval and modification of tutorial configuration files
- 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. We have developed backend services and repositories that are hosted on our campus cloud services.

### *A. Current Progress*

We have made significant progress toward generalizing the *AM Training Tutor*. We are now able to load all tutorial assets from a remote service by consuming configuration information provided by a remote service. By altering properties provided in the configuration file, we are also able to modify the tutorial without recompiling the VR application. We have created web services that can be deployed using continuous integration to the cloud and can be invoked from any remote location. This provides the first step to transforming the *AM Training Tutor* to a cloud-based production system that can simultaneously support multiple tutorial configurations and *AM Training Tutor* instances deployed on multiple VR devices. Moreover, we have started developing a web application to build tutorial configurations.

### *B. Challenges*

The major challenge we currently face 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. This is likely to have a significant negative impact on user experience. We are currently exploring several options in order to minimize this loading time. One option is reducing the quality of the 3D textures or replacing them with color codes within the VR application. While this can reduce loading time to under a minute, the loss of quality may be significant enough to impact user experience. We are exploring an option where we can strike a reasonable balance between loading time and 3D texture quality.

We intend for the tutorial configuration builder to be used by 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. For instance, while prompting a VR developer for the position coordinates of a game object sounds natural, it is not necessarily so for an AM expert. To address this challenge, we intend to provide a high-level description of each component that can be configured using the web application. It is also likely that our configuration builder will require at least limited assistance of a programmer, or an expert in VR applications. While we will make every effort to reuse 3D assets across all AM machines, some properties or textures are specific to individual AM machines. Thus, we will have to develop new artwork for new AM machines.

This task cannot be avoided. Nonetheless, as all assets are loaded from a remote location based on a configuration file,

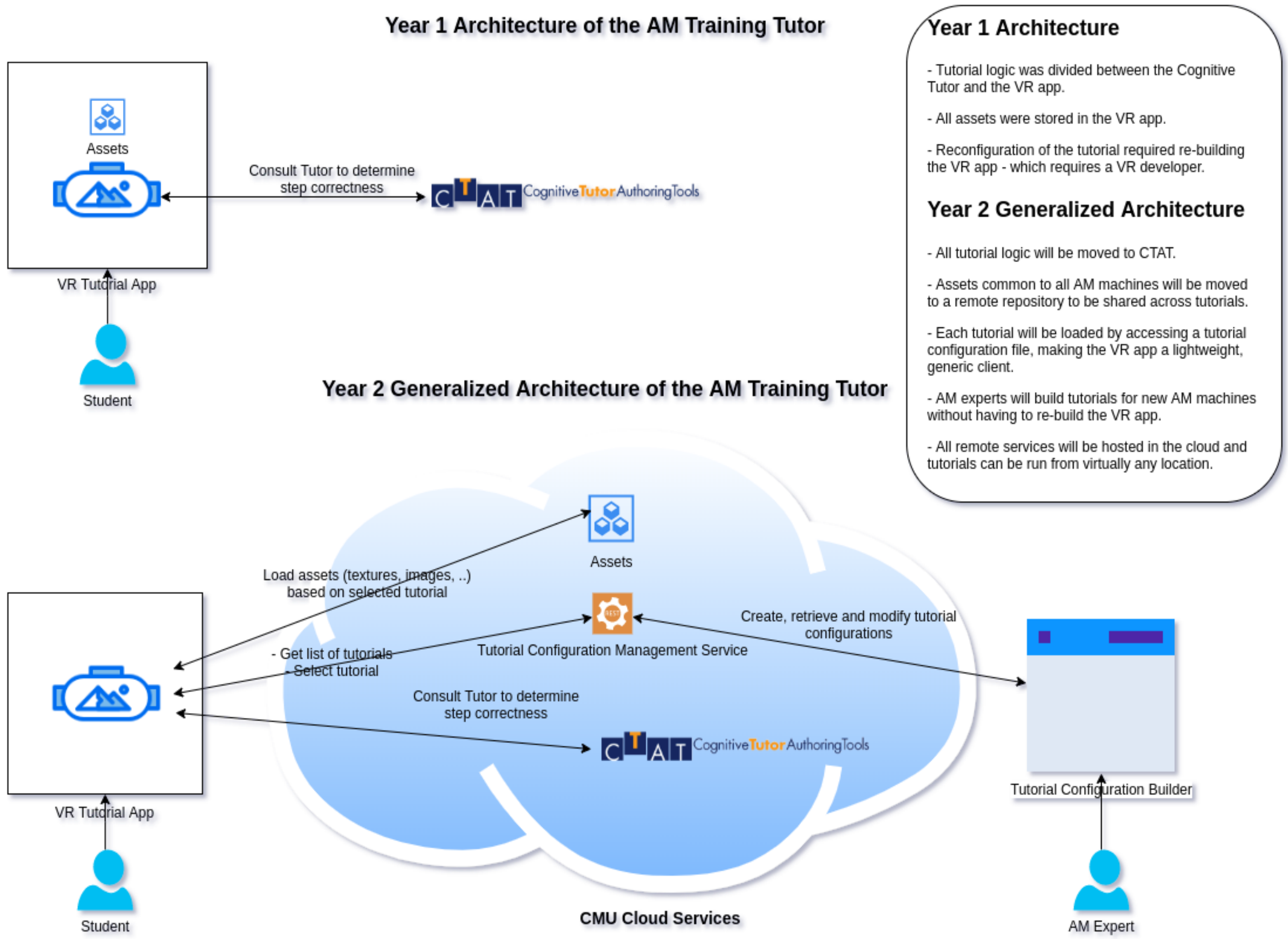


Fig. 2. Comparison of the previous and current AM Training Tutor architectures

addition of new assets will only require modification of the configuration file. In this manner, we will be able to avoid recompiling the VR application.

## IV. Conclusion

By generalizing the *AM Training Tutor*, we believe we can build instructional systems for similar AM equipment in much less time than it took to build the initial system. To test the generalization, we plan to create a new tutorial for the ExOne Innovent in our campus AM laboratory. Achieving this milestone will demonstrate how to successfully repurpose and generalize existing training systems. Further, we anticipate 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 we have developed, we will iteratively test the technology with a variety of users including students, AM technicians and engineers working at CMU as well as those in industry.

## V. Acknowledgments

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