Remotely Accessible 3D Printer for Teaching CNC Programming: Lessons Learned

Dr. Sheng-Jen "Tony" Hsieh, Texas A&M University

Dr. Sheng-Jen ("Tony") Hsieh is a Professor in the College of Engineering at Texas A&M University. He holds a joint appointment with the Department of Engineering Technology and the Department of Mechanical Engineering. His research interests include engineering education, cognitive task analysis, automation, robotics and control, intelligent manufacturing system design, and micro/nano manufacturing. He is also the Director of the Rockwell Automation laboratory at Texas A&M University, a state-of-the-art facility for education and research in the areas of automation, control, and automated system integration.

Remotely Accessible Ultimaker 3D Printer for Teaching CNC Programming: Lessons Learned

Abstract

Remote labs can provide authentic and self-paced learning experiences and help to overcome barriers to learning such as high equipment cost and limited lab time.. The paper describes the development of a remotely accessible Ultimaker 3D printer and learning materials for learning CNC programming to enable remote learning. A 3D printer is similar to a 3-axis CNC machine in having X, Y, and Z axes, but is more affordable and versatile. Users can either run an entire CNC program as a job or run a segment of code at a time. The materials were evaluated by students during the lab time. Students responded positively overall to the remote access tool and to seeing the real-time response of the printer to the G-code; and expressed a desire for more time to play with the system. Student suggestions included providing a better view of the position of the tool tip. Future directions include splitting the program into subroutines so that a sub-routine will be executed only when requested, rather than loading the entire program at the beginning. We will also provide a better view of the 3D rendering model using multiple images from webcams positioned at different locations in the machine work envelope.

Motivation and Related Work

Most manufacturing engineering-related courses—such as Manufacturing Process and Control, Industrial Welding, CAD/CAM, and CIM—include a laboratory component. Labs help students gain experience in using real and industrial-scale equipment. However, lab time is often limited, students often have to share equipment, and labs need to be completed in a fixed time. As a result, some academic institutions are interested in using remote lab experiences to complement or supplement local lab experiences [1-2].

Additive manufacturing (AM) systems—which provide 3D printing process—have received much attention in recent years due to their flexibility in making parts ranging from simple to complex, ease-of-setup for production, and ease of maintenance. There are many publications published from a research perspective [3-5], and a few from an educational perspective. The focus of this paper is on use of remote laboratories for 3D printing for educational purposes.

Lan [6] provides a comprehensive review of research on web-based rapid prototyping and manufacturing (RP&M) systems that describes various architectures and key issues, and reviews tools to to assist with various aspects of RP&M implementation, such as (1) RP&M process selection, (2) RP price quotation, (3) STL Viewer, (4) RP data pre-processing, (5) job planning and scheduling, (6) remote control and monitoring for RP machines, (7) security management, (8) applying new technologies and concepts to the systems. Fidan [7] describes development and implementation of remotely accessible rapid prototyping laboratory. Fidan and Baker [8] incorporated a remote prototyping lab as part of a STEM Academy for high school teachers. Hsieh [9] described a remotely accessible system consisting of a Stratasys Dimensions SST 1200es printer, work-flow processing, and remote viewing components. Students can submit a job after a credential check. The STL file is sliced and uploaded to the 3D printer. Students can view the part being made via webcam and streaming via internet video-sharing providers. Survey results suggest that the students found the system to be very relevant to their education and would like to see more tools and systems like this made available. Hsieh [10] described the design, assembly, and evaluation a MTW 3D printer for teaching different manufacturing education concepts such as Robot Welding and CNC programming. The system utilized open source code to allow user remote access to control and operate on the system. Evaluation results and students' comments suggest that the approach is valuable to their education.

Computer numerical control (CNC) concepts and knowledge are often covered as one topic in CAD/CAM, CIM, or production system courses. Within the topic, concepts and knowledge of numerical control (NC), NC part programming, DNC, CNC, and adaptive control are addressed. During lab time, students learn to use CAM software to design a work piece, machining steps, and required cutting tools. The CAM software can simulate how the work piece will be cut; if everything looks good, users can post-process the job into CNC code. They can then upload the code to a CNC machine and observe the part being cut in real time. CNC machines are often expensive; a new 5-axis Haas CNC machine can cost up to $250,000. Most departments can only afford a few of them. As a result, students in large classes often experience bottlenecks while waiting to cut their parts.

The goal of this effort was to alleviate the bottleneck and increase access to needed equipment by allowing users to learn about CNC coding by remotely controlling an Ultimaker 3D printer. Users can register and login to the system, and make an appointment to use the 3D printer. Users can verify the CNC code line by line as well as entire CNC job via a web based graphical user interface and monitor the printing process via two different webcams mounted at different positions of the 3D printer.

Development Tools

Tools used to set up and control the remote printing process included the following:

- **Webpages**: PHP, JavaScript, HTML
- **Database**: Access
- **Background control program**: VB.NET
- **Webserver**: Apache, Amazon Web Services (AWS)
- **3D printer and controller**: Ultimaker 3D printer
- **3D printer control program**: https://ultimaker.com/software/ultimaker-cura
- **Required software**: Windows Operating System; AWS (Amazon Web Services); Net Framework 4.7; Visual Studio 2017

System Architecture

Figure 1 shows the components of the remote Ultimaker 3D printing system. Figure 2 shows the architecture of the client web page. Both desktop and mobile users can interact with the web server via the client web page. The web server is connected to the Ultimate 3D Printer and a D-Link webcam. The webcam provides real-time images to the remote client while the 3D printer is printing. As shown in Figure 3, one webcam provides a top view of the 3D printer and the part being made; the other, which is mounted on the front-right corner column, provides an isometric view of the printer.

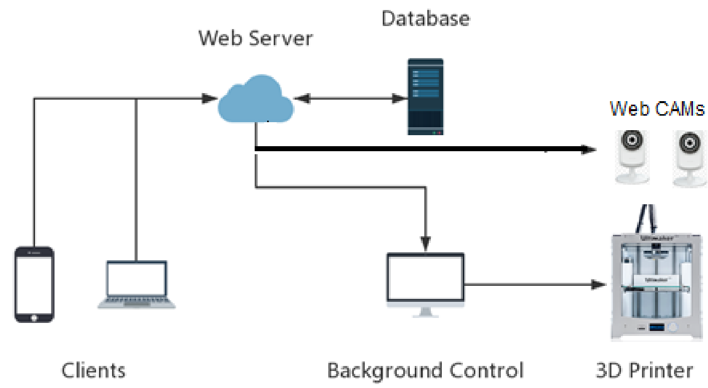

Figure 1. System Components

Client Webpage Architecture

Figure 2 shows the architecture of the web page design. From the first page, a user can register to obtain an user name and password to login to the system. The user can also request a password to be sent to if she/he forgets the password. On the Printer main page, users have four options, namely, (1) View Temperature, (2) Print, (3) Camera Feed, or (4) Manual Movement. There are additional options within each sub-menu. For example, the View Temperature web page allow the user to view the bed temperature as well as extruder temperature.

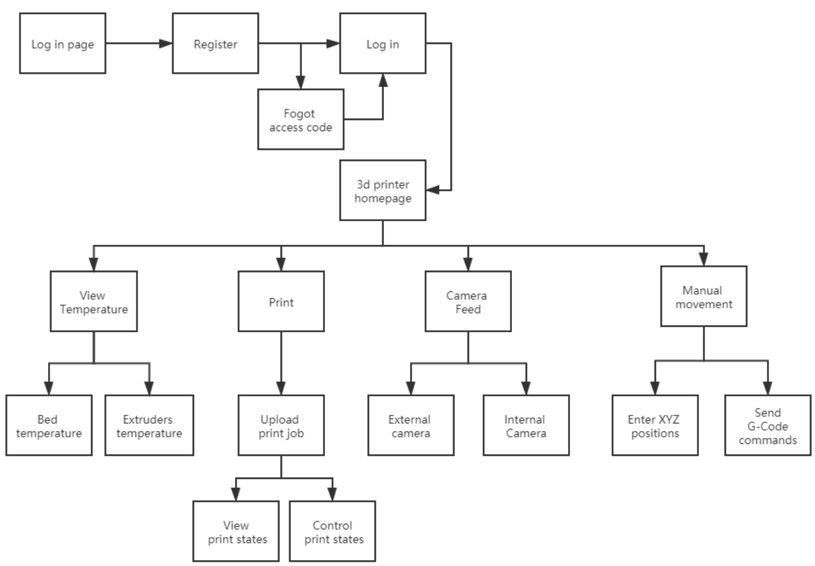

Figure 2. Client Webpage Architecture

Figure 3. 3D Printer and Webcam System Setup

Remote Interface

New users need to first register for an account in the system. After logging in, they need to register for a one-hour time slot to access the printer. In the current setup, live streaming is presented using an D-Link IP camera. On the main page, user can view process parameters such as Bed Temperature and Extruder Temperature. Also, user can upload jobs to be printed. Once a job is uploaded, the bed temperature starts to rise. When it reaches a pre-set temperature, the printer head will start moving to print the part; users can to Pause, Resume, or Abort the job. Users can click on the Camera feed option to select a different camera to provide a different angle view of the part. Lastly, users can also click on the Manual Movement function, which leads to a web page that allows G-Code to be entered to move the printer head to a new location.

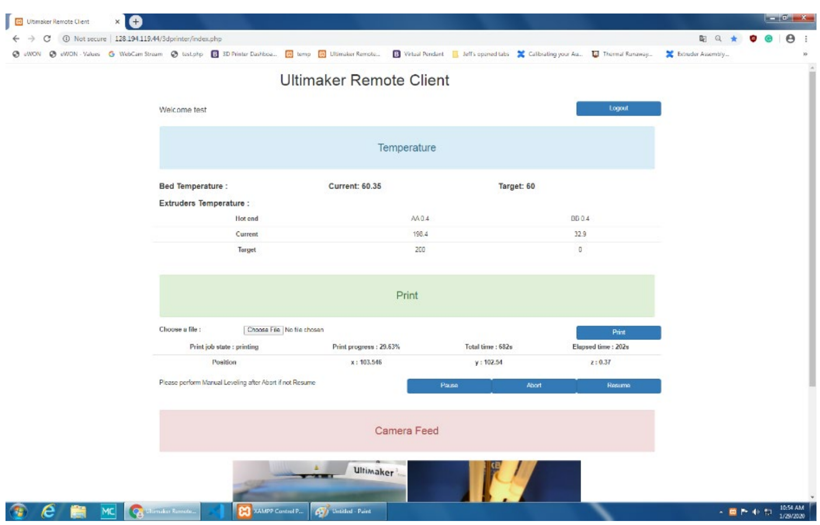

Figure 4. Remote 3D Printer Main Page After Login.

Figure 5 shows the Manual Movement web page. The empty textboxes allow entry of new coordinates either by typing them into the provided form fields or by using G code. In either case, the printer head moves to the desired location after the user presses Submit.

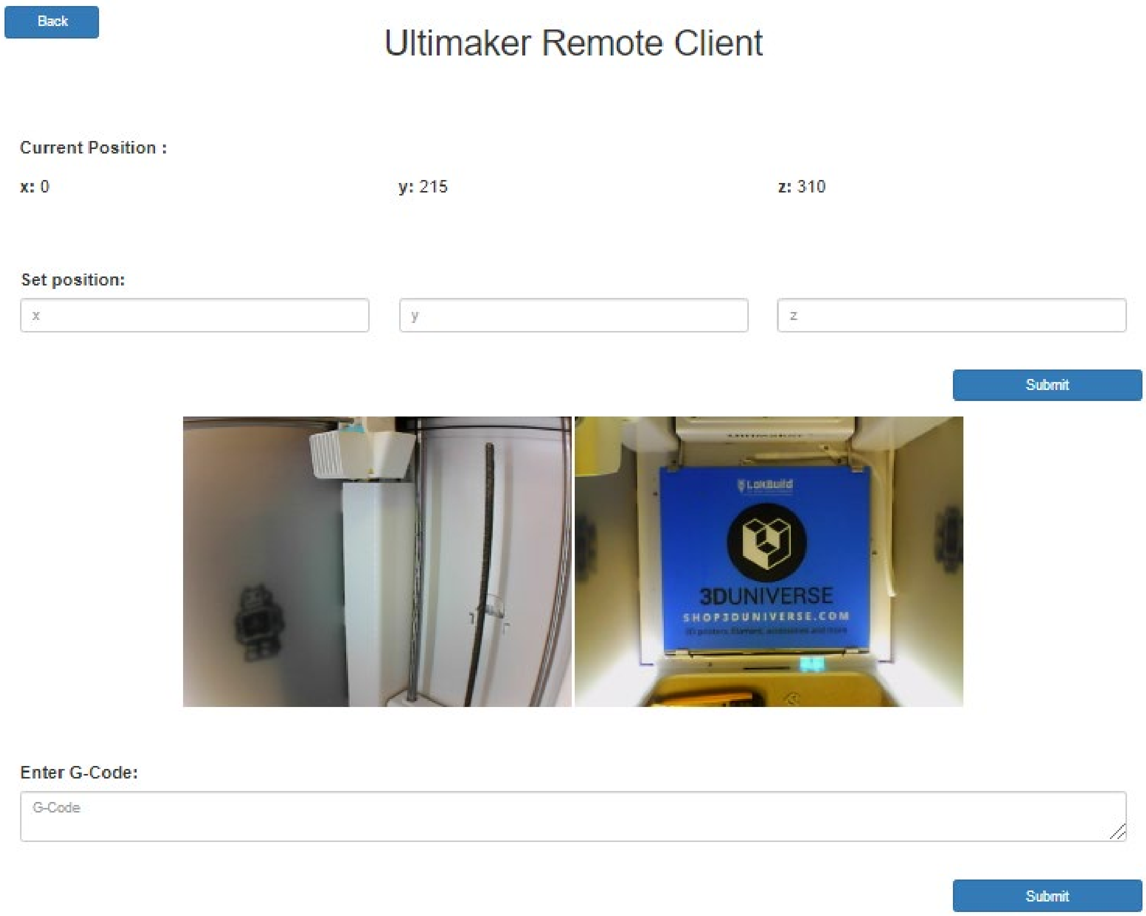

Figure 5. 3D Printer Dashboard

Figures 6 and 7 show the layout of the web pages when using a mobile device. The functions are all displayed on the screen and users can scroll up or down to navigate to needed functions.

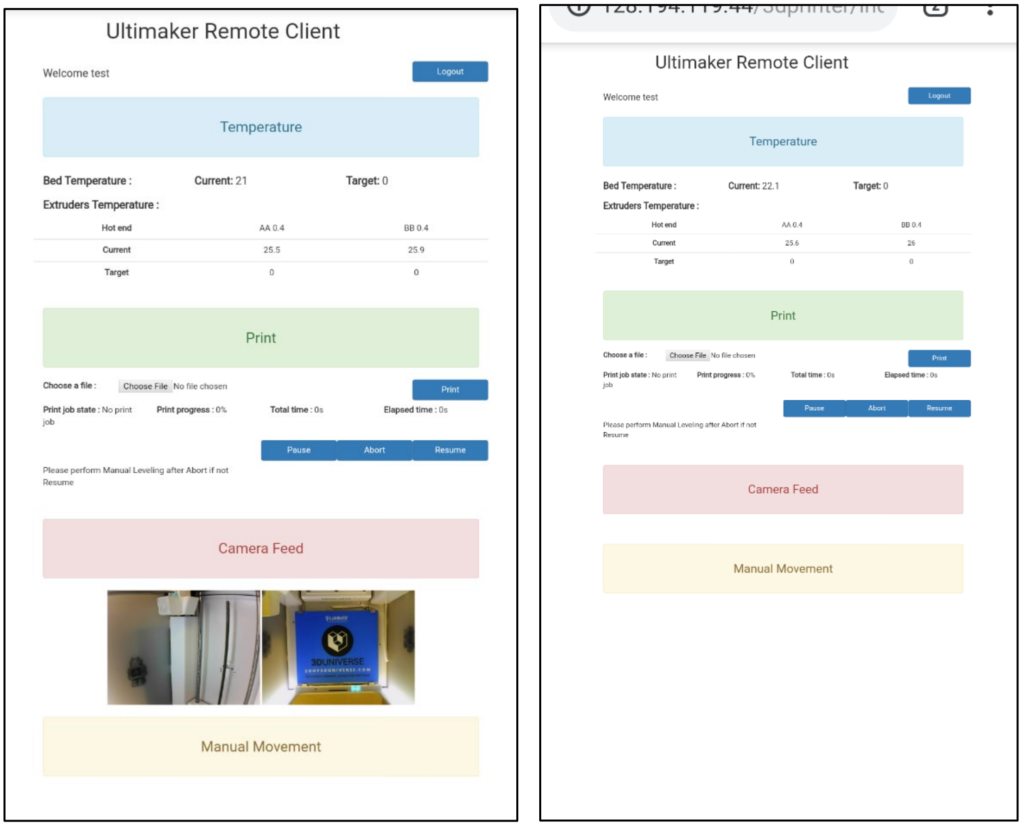

Figure 6. Client Main Web Page showing on the Mobile Device.

Figure 7 shows a Texas A&M being printed on the printer bed after the file has been uploaded.

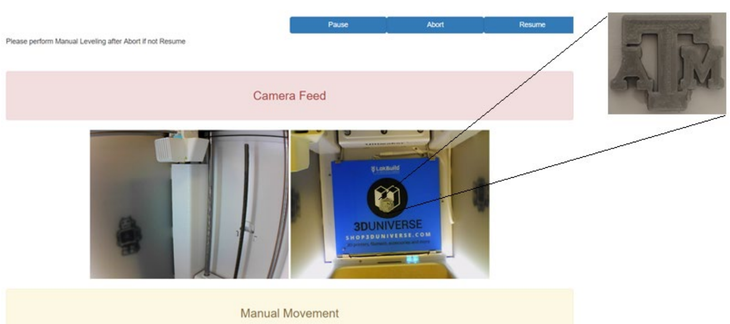

Figure 7. Uploading a file in Upload mode to print a logo.

Evaluation

Participants. Participants in this evaluation were 51 undergraduate students enrolled in a Manufacturing Automation and Robotics course where they were learning about programmable logic controller, sensor technology, interfacing, industrial robot, and machine vision. Evaluation activities took place in the first week of the semester.

Materials. Students watched a teaching assistant demonstrate how the system works and viewed a video with captions describing the entire CNC printing process. Then they followed lab instructions to complete a CNC coding exercise. The exercise required them to enter CNC code one line at a time and observe how the printer head moves from point 1 to point 2 based on the CNC code. The exercise is below. In preparation for the exercise, a marker should be attached to the printer head and the printer recalibrated to (0, 0, 0). Figure 8 shows the print head attached to a black marker. Figure 9 shows the completed drawing.

Task #3.2 G-Code practice

Theoretically, a 3D printer is a type of CNC machine and it indeed uses G-code to move its tool (extruder) around.

In this task, the goal is to use G-code to move the extruder in two ways: a linear motion (G1) and a counterclockwise arch motion (G3).

1. Go to the “Enter G-Code” section at the bottom.
2. Type “G28” and click “Submit” at first.
3. Type “G0 X130 Y50” and click “Submit”.
4. Type “G3 X50 Y130 I-80 J0” and click “Submit”.
5. **Screenshot at this point.**
6. Type “G28” and click “Submit” to home it back.

Figure 8. Setup of the 3D Printer Head for CNC programming Exercise.

Figure 9. Finished Drawing after CNC Exercise.

After the lab exercise, students completed an opinion survey. This survey asked students to rate various characteristics of the prototype on a 7 point Likert scale. Students rated features, objectives, use of multimedia, instructional sequence, interaction with computer, emphasis on important information, relevance to education, and overall quality.

Opinion Survey

Overall the responses were very positive (mean: 5.72, min: 5.52, max: 5.90), especially for the item "I would like to have more tools like this available to help me learn."

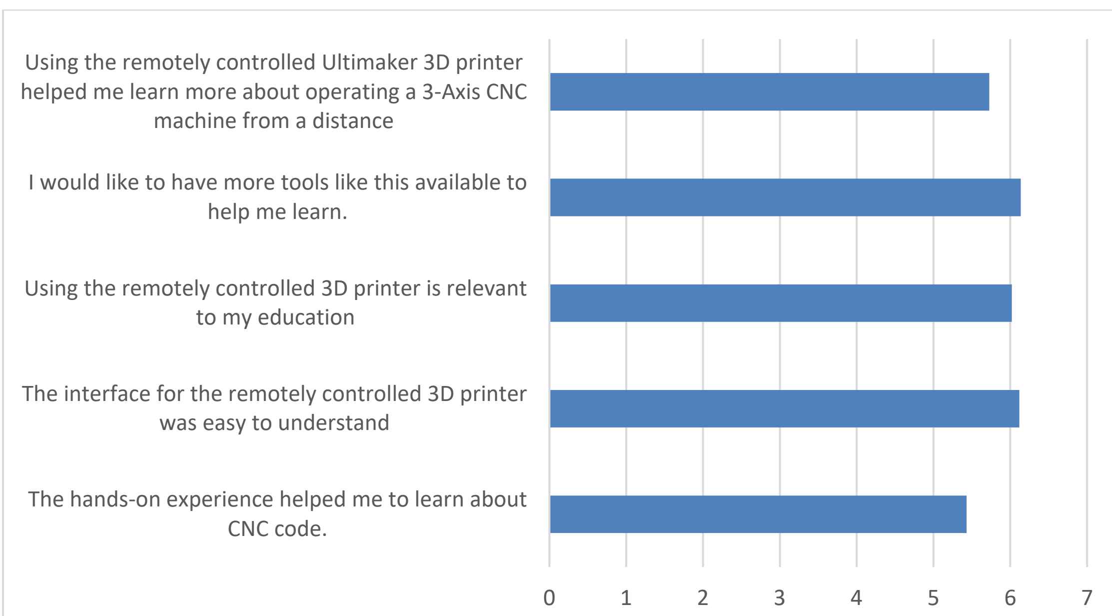

Figure 10. Mean responses to opinion survey questions.

Summary of students' comments

Students were asked to identify the most helpful thing about the technology and things that can be further improved.

Most helpful things about the technology. Following are the sample of responses:

- Using remote access
- G-code experience
- It's a relevant application of what we learn in calss/lab
- Able to see each output after each command
- Learning G code
- The step by step process
- Nice to learn real world applications
- How important it is to have proper code
- Seeing lecture material in real life
- Being able to see the printer execute commands immediately
- Camera feed/previous knowlege
- The simplicity and real time look at the printer's movements
- Hands-on experience is always better
- Using G-code!
- Interesting concept
- Seeing it work live
- There is hands-on and instant feeback from the camera views for the 3D printer
- Realizing that 3D printers run G code

Things to be improved:

- The website didn't reset each time submit was pressed
- More time
- Larger variety of examples
- We got to play around with a little more
- More task like this
- Better camera angle
- More in-depth

Conclusion and Future Directions

Overall, students have responded positively to using the remotely accessible 3D printer. Suggestions include reducing the time delay and providing a better view of the position of the tool tip. Future directions include splitting the program into subroutines so that a sub-routine will be executed only when requested, rather than loading the entire program at the beginning. We will also provide a better view of the 3D rendering model using multiple images from webcams positioned at different locations within the machine work envelope. Finally, we will conduct a formal assessment of students' learning.

Acknowledgements

This material was supported by the National Science Foundation's Advanced Technology Education Program (award no. 1304843). Any opinions, findings, and conclusions or recommendations expressed in this material are those of the author and do not necessarily reflect the views of the National Science Foundation.

Bibliography

[1] Hsieh, S. "Design of Remotely Accessible Automated Systems to Enhance Industrial Automation Education," *ASEE 2017 Annual Conference, June 25 - 28, Columbus, Ohio*.

[2] Grodotzki, J., Ortelt, T.R. and Tekkaya, A.E., 2018. Remote and Virtual Labs for Engineering Education 4.0: Achievements of the ELLI project at the TU Dortmund University. *Procedia Manufacturing*, *26*, pp.1349-1360, 2018.

[3] Bikas, H., Stavropoulos, P. and Chryssolouris, C., "Additive manufacturing methods and modeling approaches: A critical review," *Int. J. Adv. Manuf. Technol*., 83(1-4), pp. 389–405, 2016.

[4] E. C. E. Costa, J. P. Duarte, and P. Bártolo, "A review of additive manufacturing for ceramic production," *Rapid Prototyp. J.,*. 23(5), pp. 954–963, 2017.

[5] J. Deckers, J. Vleugels, and J.-P. Kruth, "Additive manufacturing of ceramics: a review," *J. Ceram. Sci. Technol*., vol. 5, no. 4, pp. 245–260, 2014.

[6] Lan, H.. "Web-based rapid prototyping and manufacturing systems: A review." *Computers in industry*, 60(9), pp.643-656, 2009.

[7] Fidan, I. "Remotely Accessible Rapid Prototyping Laboratory: design and implementation framework," *Rapid Prototyping Journal*, 18(5), pp.344-352, 2012.

[8] Fidan, I. and Baker, J. Designing the Future: Integrating cutting-edge design and manufacturing tools into 9th and 10th grade STEM education. 2013 ASEE Annual Conference, June 23-26, Atlanta, GA.

[9] Hsieh, S., Goldammer, K.J., Fleming, B.M., Crowder, R.R., Wiser, R.S., Elanany, E., and Hogan, M., "MAKER: Setup and Evaluation of Remotely Accessible 3D Printer for CAD/CAM and CNC Courses," *ASEE 2017 Annual Conference, June 25 - 28, Columbus, Ohio*.

[10] Hsieh, S. (2019, June), Lessons Learned from Remote Access 3-D Printing Machine for Manufacturing Education," *ASEE 2019 ASEE Annual Conference & Exposition, June 15 - 19, Tampa,* Florida. https://peer.asee.org/33061