Cook Engineering Design Center

# Final Design Review

*Submitted in partial fulfillment of the requirements for*

ENGS 90: Engineering Design Methodology and Project Initiation

# Machine Shop Instruction Tool

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*Sponsored by*

## Thayer School of Engineering

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## Executive Summary

At the Thayer School of Engineering at Dartmouth, it is a requirement for every entry-level Engineering major student to take a series of instruction classes to learn how to use the tools in the machine shop for future projects. However, there are a limited number of supervisors and hours available at the shop for these students. This team has worked closely with its sponsor, Nicholas Edwards from the Thayer Machine Shop, to develop an innovative way to teach students how to use these tools. A digital learning solution has been developed to supplement the machine shop's training that students can access online anytime and anywhere. There is a large potential market for this product, both for engineering schools and in industry.

After in-depth research - including identifying existing state-of-the-art solutions; shadowing instructors at the machine shop; contacting machine shops at other universities; and, analyzing user behavior - the team decided to focus on instructional videos and a software simulator for the lathe. At Thayer, professors use instructional videos to supplement their teaching. The machine shop uses videos to help train its teaching assistants. The team found that complex tasks, like learning to fly or perform surgery, also incorporate simulation. Based on these research findings and the original requirements, the team chose design parameters for a comprehensive online teaching tool for the machines in the shop.

With the original design requirements, the team focused on creating an initial prototype for just the control of the lathe. Users were tested to determine the best combination of different design elements – videos, simulation, and textual instructions – to include in future iterations. From the initial tests done during ENGS 89, videos and simulation were found to be the most beneficial. In order to create a more realistic simulation, a 3D simulator was incorporated into the existing prototype during ENGS 90 and the online curriculum was expanded. Users are able to see how their online interaction with the lathe controls would affect the cutting material.

This new and revised model was tested primarily on students from ENGS 21 who had not used the lathe before. The team found that access to the videos and simulation improved the user's learning performance. In addition, giving the students access to higher quality videos than those used during the initial tests also improved performance. Feedback that users provided on the surveys helped the team to revise the product before its final deployment.

For future use of the online tool at Thayer and elsewhere, the team consolidated all of the components needed to use and maintain the software on a GitHub repository. These components included the hosted webpage, the code repository, and documentation. The documentation contained details for maintaining the current version and expanding it to other tools. The team also contacted other schools and companies to evaluate the potential impact of the software on the market and received some positive feedback.

In the future, this tool will primarily be used and maintained by the Thayer Machine Shop. However, it can be extended to other machine tools and be used by machine shops in other academic settings and in industry. In conclusion, the team achieved its initial goal of creating a safe and effective machine instruction tool that can be used remotely and helps to improve the user's learning experience. The solution met all the requirements from the sponsor.

**Acknowledgements**

We had a lot of support from Thayer School of Engineering during the course of our project. The machine shop and its staff allowed us to use their facilities to test users and offered support. Professor John Collier connected us with ENGS 21 students who volunteered their time to test our product. Professor Ryan Halter served as our course advisor and provided valuable feedback during the two terms that we worked on this project. Professor Stephen Taylor worked closely with us and provided strategic and technical feedback, including over the winter break as we continued to make progress on the project. Nicholas Edwards, our sponsor from the Thayer Machine Shop, was working with us every step of the way, providing valuable feedback and active support throughout our work. We would like to thank all of those involved. We would not have been able to achieve the same level of quality on this project without your help.

# Contents

# I Overview

## I.1 Introduction

At the Thayer School of Engineering at Dartmouth, it is a requirement for every entry-level Engineering major student to take a series of instruction classes to learn how to use the tools in the machine shop for future projects. In the Fall 2018 term, there were over 100 students who received machine shop training for ENGS 21, ENGS 76, and other courses [1]. There are four full-time shop staff members who oversee all of the training and supervision for these students each term, providing a host of training sessions [2]. Given the short amount of time that students are able to spend learning to use these tools and the level of care it takes to operate them, an additional way to help teach students would be beneficial.

The team has developed a digital learning solution to supplement the machine shop's training curriculum that students will be able to access remotely anytime and anywhere. This solution will improve how efficiently the machine tools are taught, reduce the time needed to educate each student, and possibly give more students time to learn in the machine shop. In addition, the team has delivered a code repository and documentation to the machine shop (see section III).

During ENGS 90, the team focused on how students in ENGS 21 learn and practice with the lathe. In the future, this solution can be extended to other machines and courses at Thayer. Students will be able to apply their knowledge to their future engineering projects.

## I.2 Problem Statement

The opportunity for students at Thayer and other colleges to learn and practice in the machine shop is limited by the number of hours that the shop is open and the availability of instructors to teach them.

## I.3 Need Statement

As technology advances and machine education progresses, the machine shop would like to incorporate new learning techniques into its teaching. In particular, the shop would like an instructional online learning tool that students can complete remotely before entering the shop so they arrive more confident and prepared. In addition, such a tool will allow students to practice as long as they want, without instructor supervision, in order to become more proficient on the machines. With these goals addressed, instructors at the machine shop will be able to teach to more prepared students and possibly accommodate more students in the future.

### I.4 Accessing the Product

While reading this report, the reader may want to interact with the software. The final software product can be viewed here [3]:

`https://machine-tool-simulator.github.io/Simulator-Web-Client/`

The code and documentation are available here [4]:

`https://github.com/Machine-Tool-Simulator/Simulator-Web-Client/`

## II Methodology of Approach

### II.1 Alternatives and Research

#### II.1.A State of the Art

At Thayer and other schools that were contacted (including U.C. Berkeley and Cornell), the current state of the art includes having students attend supervised machine shop learning sessions before they are allowed to use the machines on their own. Outside of college instruction, research of current machine instruction tools identified two main state-of-the-art solutions:

1. There is a patented mechanical device that can be used for machine tool simulation [5]. The mechanical simulator is interesting, but not universally accessible like an online program would be on the Internet.
2. Online tools can be used by advanced users to simulate cutting out vector files that could also be uploaded to the machine tool [6]. The online tools are useful for advanced users, but do not have a learning component for people who are new users of the machines.

This project aims to provide a solution that combines the above two approaches - one that would be useful for beginners and allow interaction like the mechanical device, but also accessible remotely and realistic like the online simulators.

### II.2 Design Development

#### II.2.A Application of Industry Standards

The team made the design decisions based on the industrial standards outlined by the Association for Computing Machinery (ACM) in order to provide reliable and useful software to help educate students in a more efficient manner [7].

The team looked at not only the requirements and deliverables specified by the project sponsor, but also took the results from the trade studies conducted during the Fall 2018 term into consideration. Consequently, the team focused on the development of the simulation software combined with high quality educational videos. The results from the trade studies confirmed that both of these features were beneficial and constructive in helping users understand the fundamental knowledge needed to operate a lathe machine.

### II.2.B Documentation

Based on the deliverables, the team has included documentation on how the code should be maintained in the future (see section III). As is standard with other software projects, the team included a "README.md" file as part of our final code repository on GitHub [4]. As part of the design, the team carefully considered which components are necessary for future developers to take advantage of the software. As a result, the documentation was structured to address the following concepts:

- **Usage** - details on how users (e.g., a student) can access the software on their computers.
- **Implementation** - includes brief summaries on the overall structure of the code, the user interface, the videos and instructions, the 3D simulator, the control, and task checking.
- **Maintenance steps** - includes details for developers on how to add additional material to the lathe curriculum and expand the software to include other tools.
- **Future development steps** - includes possible improvement ideas for future developers (although the team addressed the most important ones, there were other good suggestions for improving the software in the future included here).

## II.3 Design Concepts

### II.3.A Control Simulation

During ENGS 89, the team designed the simulation for the Prototrak control for the lathe, where all the commands are entered [8]. The control simulation allows users to simulate different functionalities of the lathe by interacting with the 3D simulation. To increase the accessibility of the software, the control simulation is implemented using the following web programming languages - HTML, CSS, and Javascript - which will allow users to access the software in any device that has browsers installed. The team used HTML to provide the basic structure of the control simulation, which was then formatted to resemble the real control display of the lathe using CSS. Javascript was used to implement the user interaction between the control simulation and the 3D simulation of the lathe.

### II.3.B Lathe 3D Simulation

The team considered flight and surgery simulators and determined that in order to make the lathe simulation as realistic and beneficial as possible, it would have to be 3D. We explored different simulators: Unity, BabylonJS, and D3 (see Table 1) [9] [10] [11]. BabylonJS was chosen because it could be best integrated with the work that had already been done, be used on any device with a web browser, and required the least overhead to run.

Table 1: Comparison of 3D Simulation Software

| | Unity | BabylonJS | D3 |
|---|---|---|---|
| Allows 3D simulation | ✓ | ✓ | |
| Works with our current progress | | ✓ | ✓ |
| Available on any web browser | | ✓ | ✓ |
| Little overhead (no large downloads) | | ✓ | ✓ |

### II.3.C Mobile

In accordance with the goal for the software to be available online anytime and anywhere, the product was ported to mobile. This process was not difficult beecause BabylonJS is compatible with mobile browsers. After adjusting elements of the page to fit on mobile devices, the result was an appealing solution that could be interacted with through touch and is portable (see Appendix D).

## II.4 Testing

### II.4.A Initial Test Summary

Last term, the team tested a preliminary group of students that were divided into three groups: (1) Video and simulation (hybrid); (2) Simulation only with textual instructions; (3) Video-only.

Users that were placed in each of these groups were tested based on their retention when they applied what they remembered in the machine shop. They also provided survey responses. The results from the tests supported two hypotheses: the simulation improves the learning experience, and videos are better than textual instructions alone (see Appendix E). Both the objective and qualitative test results showed that the hybrid solution of videos and a software simulator delivered the most effective learning experience for the students, in terms of their performance and user satisfaction.

The team wanted to refine the product and verify that the changes were beneficial. Based on the results from ENGS 89, the team focused on the simulation-video hybrid solution (which will be referred to as the Machine Tool Simulator or MTS for the remainder of this report) and did not include the textual instruction group when conducting the new tests. Also, during ENGS 89, there was no 3D component to the simulation. Consequently, results from testing after the 3D simulation was incorporated were compared to those results from the Fall 2018 term.

Before doing extensive testing this Winter 2019 term (primarily on ENGS 21 students), the team conducted detailed pretests on three users to refine the testing methodology and address issues. The team was able to improve a few pages that users were not able to pass, as well as become fully prepared to do multiple testing sessions with ENGS 21 students in quick succession.

### II.4.B Hypotheses

The team divided the three test groups during this analysis according to the amount of material they received as follows:

- **MTS** (Machine Tool Simulator): received the full package of videos, texts, 3D interactive simulators and the simulated controller.
- **Text-only**: received the material with the simulation and textual instructions.
- **Video-only**: received the material with only the videos.

The testing done during ENGS 90 was performed to examine the following three hypotheses when testing students in the machine shop:

- **Hypothesis I**: The MTS group has a better learning outcome in terms of their accuracy, indicated by the number of tries until successful completion.
- **Hypothesis II**: The MTS group has a better learning outcome in terms of their proficiency, indicated by the time taken for each task.
- **Hypothesis III**: Both the MTS and the Video-only learning materials have improved from the initial prototypes, indicated by better learning outcomes from the students during this iteration of testing.

### II.4.C Sample

The two groups this Winter 2019 term were (see Appendix F for the view each group saw of the tool when testing): (1) MTS, and (2) Video-only.

Table 2 summarizes the backgrounds of the volunteers during this Winter 2019 term based on their post-testing surveys (see subsubsection II.4.J). Since the team recruited participants primarily from ENGS 21, a majority were aspiring engineers in both groups, while the rest were an assortment of other students. Also, although many of the ENGS 21 students had already been in the machine shop, no one in the MTS group had any lathe experience and only a small portion of the Video-only group had experience on the lathe. In general, almost all of the participants completed the entire online tutorial before the in-shop testing.

Table 2: Engs 90 volunteer tester backgrounds

| | # Participants | % Aspiring Engineers | % Been in the Machine Shop | Users w/ Lathe Exp. | % Completed Online Before Testing |
|---|---|---|---|---|---|
| (1) MTS | 10 | 80% | 70% | 0% | 90% |
| (2) Video-only | 11 | 73% | 64% | 36% | 93% |

See more detailed background information in Appendix H.

### II.4.D Testing Procedure

The team utilized the same testing procedure in ENGS 90 as the one used during ENGS 89. The basic format remained the same. The volunteers were divided up into two groups: one with MTS and the other with Video-only. They were asked to go through their assigned learning materials before they went into the machine shop for in-person testing. However, the team changed four testing tasks from the original nine tasks used in the Fall 2018 term, as shown in Table J.1 in Appendix J. The raw data from these tests is in Appendix I.

### II.4.E Outlier Test

After running the Outlier test as shown in Table J.2, Table J.3 and Figure J.1 in Appendix J, the team found one outlier in the MTS group out of all of the samples. When recalling the tests performed with this outlier, there were indications that the individual had not properly completed the online tool before arriving at the machine shop when asked questions about it.

### II.4.F Overview Analysis after Outlier Removed

Using Minitab, the team found the average, standard deviation, and other statistics for both the number of tries taken and total amount of time taken for both groups (see Table 3 and Table 4).

With the outlier removed, the team also generated histograms based upon all of the samples and then fit curves based on the histograms. In both graphs, the further left the curve is on the graph means fewer tries or less time was taken by the users and a better learning outcome was achieved.

As shown in Figure 1, the MTS group outperformed the Video-only group by 26% in terms of the number of tries taken to successfully pass the tests. As shown in Figure 2, the MTS group outperformed the Video-only group by 32% in terms of the total amount of time taken to successfully pass the tests.

Table 3: Overall statistics for MTS (number tries and total time)

| Variable | N | Mean | SE Mean | StDev | Min | Q1 | Median | Q3 | Max |
|---|---|---|---|---|---|---|---|---|---|
| MTS numb tries | 9 | 10.333 | 0.500 | 1.500 | 9.000 | 9.000 | 10.000 | 11.500 | 13.000 |
| MTS total time | 9 | 196.2 | 22.7 | 68.0 | 108.5 | 128.4 | 200.4 | 258.4 | 289.2 |

Table 4: Overall statistics for Video-only group (number tries and total time)

| Variable | N | Mean | SE Mean | StDev | Min | Q1 | Median | Q3 | Max |
|---|---|---|---|---|---|---|---|---|---|
| Video numb tries | 11 | 13.909 | 0.967 | 3.208 | 10.000 | 11.000 | 14.000 | 16.000 | 20.000 |
| Video total time | 11 | 290.7 | 30.9 | 102.4 | 192.9 | 212.0 | 242.6 | 364.0 | 522.2 |

Figure 1: Fit curve comparison in terms of number of tries

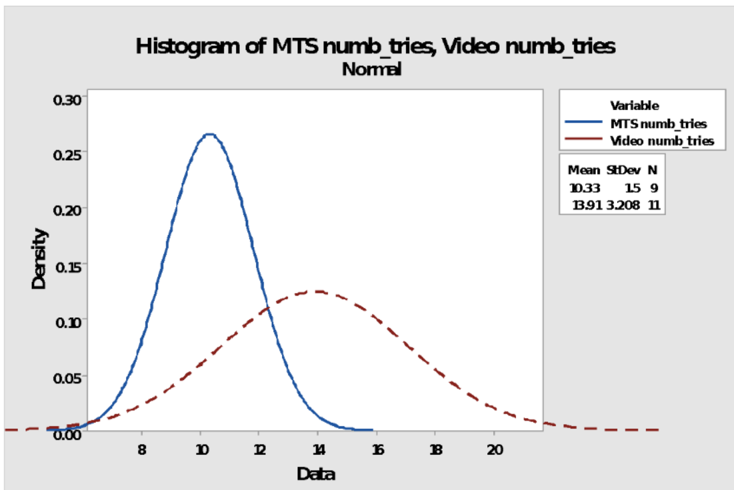
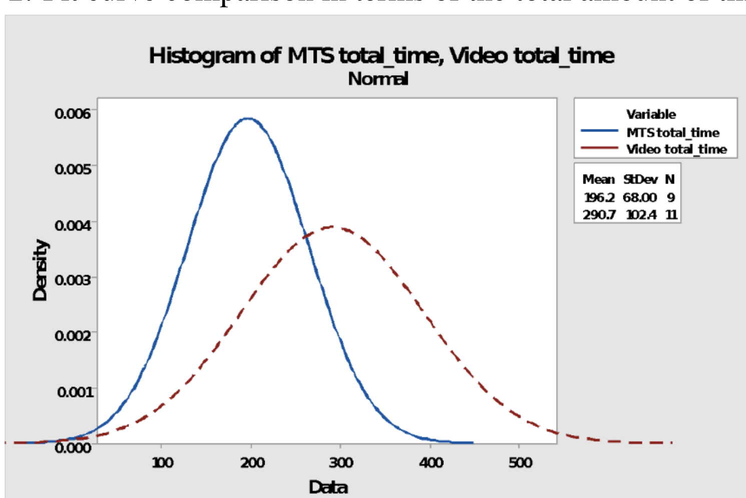



Figure 2: Fit curve comparison in terms of the total amount of time taken



### II.4.G T-tests

The team then conducted T-tests to verify if the observation from the subsubsection II.4.F about the fit curves corresponded with the fact that these differences between the MTS and Video-only groups were statistically significant.

As shown in Figure J.2 and Figure J.3 in Appendix J, both P-value are equal to or less than 0.005. This value confirms that the difference in the results between the two groups was statistically significant and the MTS did outperform the Video-only group in both the number of tries and the total amount of time taken. Therefore, both Hypothesis I and Hypothesis II were found to be true.

### II.4.H Comparison between new and old MTS and Video-only

The results from both the new MTS and Video-only groups improved since the end of ENGS 89 when the team presented its project to the Review Board. Since then, a 3D simulator built with BabylonJS was added to MTS and more videos with clearer explanations were added to the video component.

The following data analyses were conducted to verify Hypothesis III, which was whether or not both the new MTS and Video-only groups had improved since the testing conducted during ENGS 89. Four of the nine testing procedures had changed since then. The team compared the testing data from the five identical testing parts for the old and new MTS and Video-only groups. The summarized data is shown in Table 5 and Table 6:

Table 5: No. tries for old vs. new MTS and video-only groups to complete tasks on the lathe

| | MTS old | MTS new | Video-only old | Video-only new |
|---|---|---|---|---|
| Average (times) | 6.00 | 5.78 | 16.25 | 8.55 |
| Std. Deviation | 1.00 | 1.09 | 5.06 | 2.81 |

Table 6: Time for old vs. new MTS and video-only groups to complete tasks on the lathe

| | MTS old | MTS new | Video-only old | Video-only new |
|---|---|---|---|---|
| Average (seconds) | 52.84 | 72.16 | 182.49 | 142.43 |
| Std. Deviation | 27.88 | 25.09 | 42.41 | 46.94 |

For the new MTS group, the number of tries taken improved slightly when compared to the old MTS group. However, it took slightly longer for the new MTS group to complete the same tasks. This difference might have been caused by the new students being tested exercising more care, and thus taking more time, when executing the same tasks. For the Video-only group, the new version improved the number of tries by 47% and the time taken by 22% compared to the old version.

Table 5 and Table 6 illustrate that three of the four comparisons showed improved in time or number of tries since the Fall 2018 term, which indicates that the revised software solution made an apparent difference.

### II.4.I Other Details

For the new MTS and Video-only groups, the team compared the number of tries taken and time taken. This test allowed the team to identify which parts of the MTS were making the most difference compared to the Video-only version. The results are shown in Table J.4 and Table J.5 in Appendix J. For almost all of the learning parts, the MTS improved the amount of time for users to complete the tasks when tested.

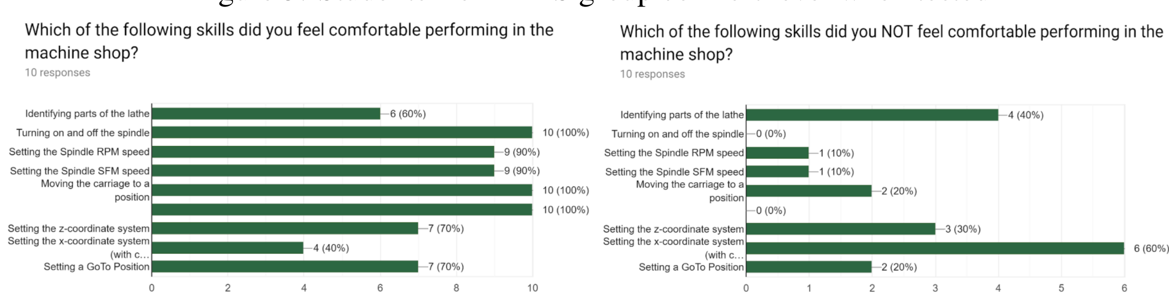
### II.4.J Survey Results

The team also sent surveys to all of the participants in order to receive qualitative feedback on both the students' backgrounds and their experience with the instructional tool. In general, as Figure 3 shows, students who had access to the videos and simulation were comfortable performing these skills except for setting the x-coordinate system (one of the most complicated tasks).

In total, 91% of the students who did not have access to the simulation said that they "would have liked to have interacted with a simulation of the tool before being tested" on their skills. From the qualitative feedback on the survey and from talking with users during testing, some aspects of the online tool that the team improved were highlighting parts when selected and skipping past certain tasks if necessary. More detailed versions of each of these results can be found in Appendix K.

In addition, for 4 of the users in Group 1, data was collected on how long these students spent on each page and the total amount of time that they spent completing the tutorial. The results showed that these students spent 30 minutes on average to complete the tutorial. This amount of time is reasonable because one of the original goals of this project was to reduce the amount of time students need to spend in the shop by 10 to 20 minutes. Assuming at least half of the time students spend with the online tool can be saved from the time they spend during the machine

Figure 3: Students from MTS group comfort level when tested



shop learning session (approximately 15 minutes), the team's goal in this area would have been accomplished. See Appendix L for a detailed table of these results for each of the 4 students.

### II.4.K Discussion

From the testing and the data analysis performed during ENGS 90, the team verified that the first two hypotheses were true. The learning outcome of the MTS did outperform that of the Video-only solution.

However, it was less clear if the result supported Hypothesis III that ENGS 90 prototypes were an improvement from those used during ENGS 89. It did seem that improving the videos from those that were used during ENGS 89 had more impact than efforts to improve the software simulation, given the amount of time dedicated to both tasks.

In the future, the decision about which solution to use is up to the machine shop. MTS might have better learning outcomes, but it would take more time to develop. If the sponsor does not want to hire a group of software developers and wants a faster solution, the Video-only solution would be the more economic choice.

# III Deliverables

## III.1 Innovation from the Project

This product is a necessary innovation because it fills a void where there is currently no economic and accessible solution of this type available on the market. This product can help the Thayer Machine Shop and improve the students' education quality because it is:

- **Accessible**: It is a pure software learning material which the users can access at anytime and anywhere as long as there is an Internet connection.
- **Economic**: Instead of hiring more teaching assistants and teaching staff to handle the increasing number of students in the machine shop, the shop could distribute this solution to its users and thus alleviate some of the demands on their time.
- **Scaleable**: The team built the product using modularity. The product currently focuses on teaching of the lathe, but it can easily be extended to other machines, such as the mill, with the current code structure.

According to Nicholas Edwards (the team's sponsor who instructed students following their use of our tool), students who had used the machine tool simulator seemed more calm and confident during the actual lathe teaching session. Students who had used the machine tool simulator seemed to have a better sense of the purpose of the lathe and needed less reminding about how to do specific tasks on the lathe. A few students commented that it was hard to remember all of the information in a video and that the simulator was helpful for making the tasks more memorable.

## III.2 Deliverables Contract

The team successfully delivered the agreed upon deliverables to the Thayer Machine Shop. The following are the main components that the team completed for the shop. See Appendix A for the more detailed deliverable contract.

1. **Software** - A working software tool that addresses certain learning goals.
2. **Code Repository** - A GitHub repository with all relevant code.
3. **Documentation** - Directions to maintain the code and apply it to other tools.

### III.2.A Objectives / Requirements

The original requirements outlined at the start of this project have each been reviewed in Table 7. The final deliverable has fulfilled all of the requirements. Detailed explanations about how it meets these requirements can be found in Appendix B.

Table 7: How requirement metrics have been addressed (see Appendix B for more description of the requirements; see Appendix J for more detail of this table)

| | |
|---|---|
| *1. Reduces time to instruct students by at least 10 minutes; as a reach, reduces by 20 minutes* - **Yes** | *2. The software opens the possibility for more skills to be taught in the machine shop* - **Yes** |
| *3. Record number of skills taught before and after software use* - **Yes** | *4. Students rate on a survey that they are comfortable with skills more than 80% of the time* - **Yes** |
| *5. Students meet 95% of the learning goals for the shop* - **Yes** | *6. Software is available >20 hours / day* - **Yes** |
| *7. Software is accessible in each of the places that we test* - **Yes** | *8. Compatible with Windows, Mac, and Linux* - **Yes** |
| *9. Compatible with Chrome, Firefox, and Safari* - **Yes** | *10. The code is modularized and a workflow and framework are developed for applying to other machines* - **Yes** |
| *11. Documentation is provided for main components: instruction, evaluation, scaling* - **Yes** | *12. A third-party reviews our repository and confirms they understand each component* - **Yes** |
| *13. All software bugs raised have been carefully handled* - **Yes** | *14. All tasks must be completed before finishing the teaching tool* - **Yes** |

## III.3 Testing Realizations

The testing process is primarily described in subsection II.4. From testing, it was determined that it takes students approximately 30 minutes to complete the online instruction tool (see Appendix L). It was verified that the students were able to perform skills on the lathe in the machine shop that they had learned online from the simulator and videos in more than 95% of the cases (see Appendix J). Students did not have trouble accessing our software. One student even wrote that it "worked totally fine and looked just like the real thing" on the survey.

The team was thus able to confirm that the deliverable could successfully alleviate some of the burden on the machine shop by: (1) teaching students certain fundamental skills needed to operate the lathe before they arrived at the machine shop; and, (2) saving valuable time because instructors would no longer have to repetitively go through basic training with every student.

## III.4 Obstacles/Risks

- **Recruiting volunteers**: During ENGS 89/90, the team had trouble finding volunteers to test the software product who did not have any machine shop training. By reaching out to Professors Taylor and Collier, the team was only able to recruit half of the target number of volunteers needed from their classes. To overcome this obstacle, the team also reached out to an assortment of other students to get enough volunteers to compile the required data.
- **Remote cooperation**: The team spent most of the winter break on developing the software product remotely. Working remotely could have decreased the productivity of the team members and caused the development of the software to fall behind schedule. To eliminate this obstacle, the team used Skype to host an online meeting each week and assigned weekly assignments to each member.
- **Potential bugs**: There were potential bugs in the software that could have undermined the learning quality of the users. If these bugs existed when launching large scale testing on the volunteers, all of the testing data could have been compromised. The team conducted a small scale pretest beforehand and identified all of the most important bugs to ensure this problem was resolved.

# IV Economic and Cost Analysis

## IV.1 Costs Associated with Project

The coding process, including writing and online researching, was negligible in terms of monetary expenses. All expenses incurred during the development of the project were incentives given to the volunteers to participate, who not only helped the team test the usability and functionalities of the software, but also allowed the team to monitor their skills on the actual lathe. The team managed to keep the cost at $500.00.

## IV.2 Market Analysis

The sponsor decided not to market the product, but instead to provide it as a free to access software. Despite this, the software can contribute value to the Thayer Machine Shop or machine shops in other engineering schools. According to the Thayer Machine Shop, teaching assistants dedicate 50% of their work time to training and learning. Their training process consists of written tutorials, video tutorials, and one-on-one training by full-time staff. In 2018, the total number of working hours for all of the teaching assistants in the Thayer Machine Shop was 8,654.65 (see Appendix N). Based on this, the total amount of wages paid to these teaching assistants would be 8,654.65*$15 = $129,820 per year. If the machine tool simulator could reduce one-fifth of the time each teaching assistant spent training (one-tenth of their overall time in the shop because they spend half of their time training) with MTS or Video-only, it could save the Thayer Machine Shop $129,820/10 = $12,982 per year.

From the old version to the new version of MTS and Video-only from ENGS 89 to ENGS 90, the team spent about 6 to 8 hours revising the videos and over 100 hours working on the software development. Given the tasks for in-shop testing, the MTS group had the best overall outcome, but only a slight improvement from ENGS 89. The outcome for the new Video-only group improved the number of tries by 47% and the time taken by 22% from ENGS 89. If the machine shop is looking for an economic way to quickly improve learning outcomes, Video-only represents a good choice. However, if they want users to reach the peak performance, then using the full instruction tool with simulation (MTS) is better since MTS outperformed Video-only by 26% for the number of tries and 32% for the time taken.

## IV.3 Costs on Larger Scale

On a larger scale, costs associated with the project would still not be high (they would be the similar to those described at Thayer). The primary cost would be hiring developers to expand the tool to other tools in the machine shop. It is possible that there could be a teaching assistant assigned to this task after the project is completed. The teaching assistant rate at Thayer is $15 per hour. If this teaching assistant worked on the project for 10 hours a week over 10 weeks, it would cost $1,500 to continue expanding the online tool each term. Further, it is possible that a school or company that used our solution might want to track data on its users, such as what steps they completed. For this purpose, it might be necessary to purchase a server.

## IV.4 Material and Part Identification

The software did not include any physical materials or parts from other manufacturers. The computers used during the development already belonged to the team members. In terms of software and libraries, the team relied on the open source JavaScript library, BabylonJS, to simulate the 3D view of the lathe machine. The library is free for public use and thus did not require any extra expense for the team.

## IV.5 Implementation on A Larger Scale

The machine tool simulator is going to be open source. The team will obtain an MIT license for this product, which will grant other developers software end-user rights such as copying, modifying, merging, distributing, etc. The software will be available for all users and will encourage third-party development and maintenance following the appropriate terms defined by the license.

## IV.6 Resources

### IV.6.A Consultants

The team worked closely with Nicholas Edwards, the project sponsor, and Professor Taylor throughout the project and had meetings every week. The machine shop staff worked closely with the team on testing the prototype and providing feedback. Kevin Baron, Lee Schuette, and Jason Downs from the machine shop also provided feedback during the course of the project. The team consulted with Tim Tregubov from the Computer Science department for technical insights on the design and implementation of the program and Professor Steven Kahl from Tuck School of Business for business advice.

# V Recommendations for Future Work

## V.1 Next Steps for Project

For the team, future steps for the project would include expanding the features of the current online tool and adding new tools. To this end, it may be possible in the future to have developers at Thayer work on addressing these components. Although the team plans to make the solution open source, there is the possibility that potential clients would like to be able to integrate the solution at their machine shop. In this case, the team could provide a service by setting up the tool for these clients to ensure that their machine shop can track if users complete all of the sections for safety purposes, which is an advantage of the product.

### V.2 Thayer Collaborators

The Thayer Machine Shop staff is enthusiastic about using the tool. They are still having ongoing discussions about where to include it in the curriculum. The shop is considering the following options:

- Using the tool to introduce ENGS 21 students to the lathe before their lathe training session
- Using the tool as a supplementary resource for educating new shop teaching assistants
- Providing the tool on iPads in the shop

Thayer Computing Services is willing to help with hosting the program as a static website without server support and to maintain the functionality only to a certain extent due to their limited bandwidth. Future students and faculty members who wish to maintain and improve the software can do so on their own with the resources provided on Github.

### V.3 Client Outreach

The team reached out to about thirty other schools and SolidWorks after incorporating feedback from users. Walla Walla University replied that they are "always interested in ways to keep [their] students safer and reduce [their] liability, as well as reduce the time and work required to give students shop training." The concept was welcomed by their lab technician and the software can potentially be put to use with modifications to the interface and tutorials to make it visually similar to the machines used there. As the team continues to await further responses, different ways are being explored to integrate the product with those schools who might benefit from it.

## VI Conclusion

This project improves how students are able to prepare for their machine shop training and allows them to continue their machine tool instruction outside of the shop unsupervised. The team completed a final prototype on which students are able to practice their skills online outside of the shop. This tool can even be accessed on a student's mobile phone.

The software program includes video demonstrations, a 3D simulation of the machine tool, and a realistic control that will provide students at Thayer with a comprehensive online teach tool to explore all aspects of the lathe. With this new online teaching tool, students will become more comfortable, proficient, and ready to use the tools before they enter the shop and they will find it useful on their projects. In the future, the team hopes to expand the tool to include other machines in the machine shop, to continue to improve functionality, and to possibly provide a service to help others in academic settings or industry who might benefit from the machine instruction tool.

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# Appendices

## Appendix A Final Deliverable Agreement

**The requirements for the final deliverable are to:**

A final deliverable that satisfies the following criteria will be made available to the sponsor (Thayer Machine Shop, Nicholas Edwards) by the group (John, Junfei, Tao, and Yuteng) by the end of Engs 89/90 in March 2018.

**The final deliverable must contain the following components:**

1. **Software Tool** - A fully functional software tool (including videos as necessary) that enables students to learn and practice these learning goals for the lathe remotely:
   - Understanding what the spindle, chuck, carriage, cutting tool, tailstock, and control are
   - Turning the spindle on and off
   - Setting spindle speed for constant Revolutions per Minute
   - Setting spindle speed for constant Surface-feet per Minute
   - Switching the control between Fine and Coarse mode
   - Understanding X and Z coordinates
   - Moving the tool in the Z direction
   - Moving the tool in the X direction
   - Establishing the Z coordinate system
   - Establishing the X coordinate system
   - Using the GoTo function
2. **Maintainable code** - A GitHub repository with functioning computer code that meets the following requirements:
   - Every function is supplemented by a comment that explains what the function does
   - All functions and variables are named semantically so the name communicates the purpose
   - Every function has only one purpose instead of many purposes
   - There are no repeated lines of code
   - There is a suite of automated tests that can be run with a single command to verify whether the application works as expected
3. **Documentation** - Instructions for how to maintain and expand the code to other tools:
   - How the code should be maintained
   - How to run the automated test suite
   - How to develop new features for teaching new learning goals
   - How to deploy new versions of the application to production
   - How to test new versions of the software on users

John Sullivan Yuteng Mei
Junfei Yu.

John Sullivan, Yuteng Mei,
Junfei Yu, and Tao Wang (3/1/2019)

Nicholas Edwards, Thayer Machine Shop
(3/1/2019)

# Appendix B Full Requirements Listing

Table B.1: Full Table of Requirements

| Type | Objectives | Requirement | Test | Metric | Rank |
|---|---|---|---|---|---|
| **Time** | **Teaching in the machine shop is more efficient** | The amount of time that it takes an instructor to teach skills to students is reduced | Time to teach the students machine shop skills is measured before and after they use software | Reduces time to instruct students by at least 10 minutes; as a reach, reduces by 20 minutes | 1 |
| | **Teaching in machine shop can be more extensive** | Instructors are able to teach additional skills in the same amount of time | Compare number of skills taught before and after students use software | Record number of skills taught before and after software use | 2 |
| **Proficiency** | **Student is able to comfortably enter formal on-site instruction** | The student is able to learn at least one of the skills necessary to use the lathe | A list of instruction skills for the lathe has been provided by Nick; at least one of these skills can be checked off without formal instruction | Students rate on a survey that they are comfortable with one of the skills more than 80% of the time | 3 |
| | **Evaluation** | An evaluation framework is provided that gauges student success | Have students use the software and evaluate their performance | Students meet 95% of the learning goals for the shop | 4 |
| **Accessibility** | **Student is able to use software anytime and anywhere** | The software / website is available for the student to download / view when necessary | Monitor the uptime of the software by periodically testing | Software is available >20 hours / day | 5 |
| | | Software can be used anywhere | Any student that we send the link to is able to access the software | Software is accessible in each of the places that we test | 6 |
| **Accessibility (cont.)** | **Software can be used on any computer** | Software works on any computer that a student might be using | Check functionality on different operating systems | Compatible with Windows, Mac, and Linux | 7 |
| | | Software works in any browser students might be using | Check functionality in different browsers | Compatible with Chrome, Firefox, and Safari | 8 |
| **Scalability** | **Software can be applied to other machines** | The software provides a framework that can be used to add other machines | Check whether a plan can be laid out to incorporate another machine | The code is modularized and a workflow and framework are developed for applying to other machines | 9 |

| | | | | | |
|---|---|---|---|---|---|
| | **Software is able to be maintained well into future** | Documentation is provided | Documentation is provided for each component | Documentation is provided for main components: instruction, evaluation, scaling | 10 |
| | | Any code used is easy for users to understand | Software is made open-source and is reviewed by others | A third party reviews our repository and confirms they understand each component | 11 |
| **Technical issues** | **Software bugs** | Bugs in the software could affect user experience | The software passes test cases that simulate real world use | All software bugs raised have been carefully handled | 12 |
| | **Unintended uses** | User should not be able to manipulate software | We have students try to pass teaching tool steps without completing individual parts | All tasks must be completed before finishing the teaching tool | 13 |

# Appendix C Screenshots of the Final Deliverable

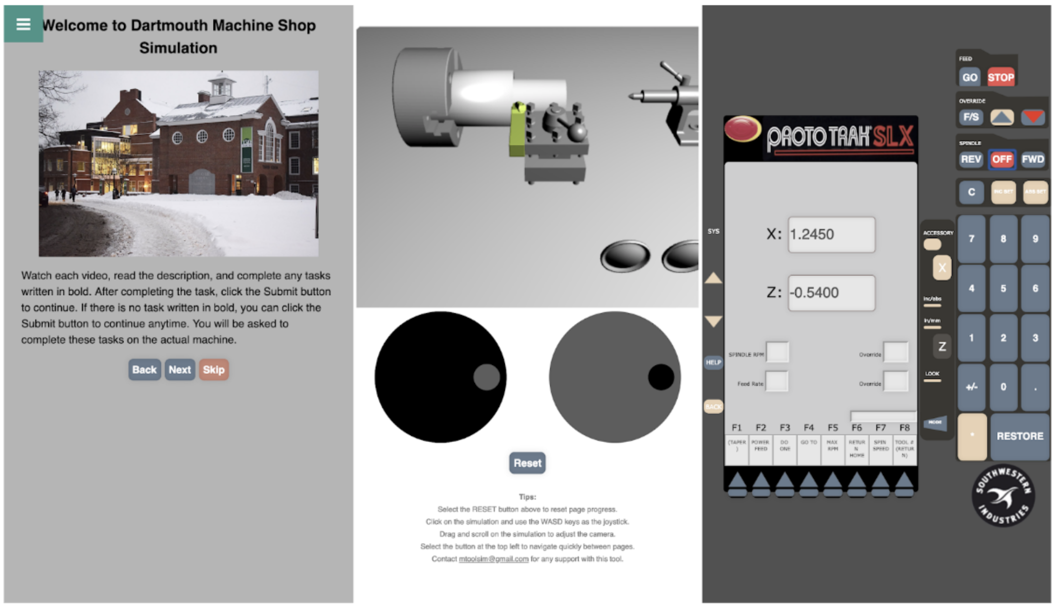



Figure C.1: Screenshot of the Final Deliverable

In the above image, the three columns from left to right include:

1. **Video and instruction displays** - Users watch the videos and instructions in this column.
2. **Simulation and wheels** - Users can modify the position of the cutting tool and cut out shapes from the material (such as in the image above) using the 2D wheels in here.
3. **Control** - The control to the left is used to enter specific commands that dictate behavior of the cutting tool and lathe material in the middle column.

# Appendix D Screenshots of Mobile Version

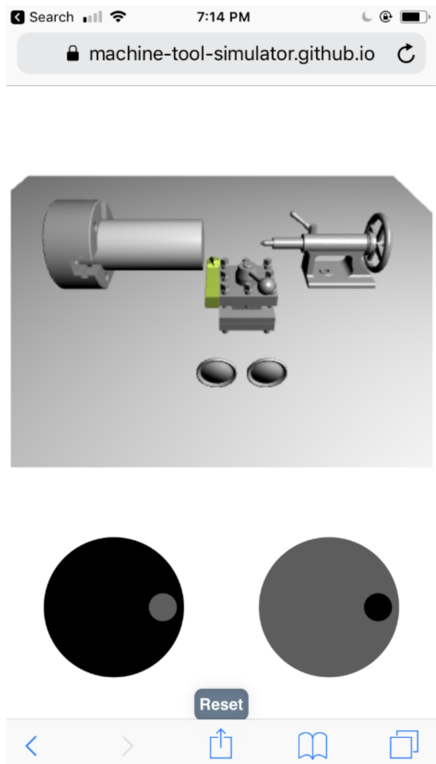



Figure D.1: Portrait Layout

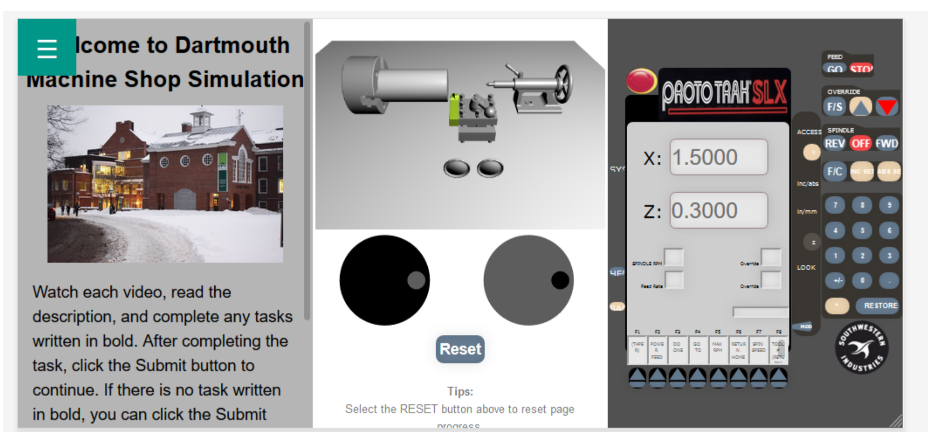



Figure D.2: Landscape Layout

# Appendix E Select Results from ENGS 89 (Last Term)

Table E.1: Raw Data Results form Engs 89 Testing

***Number of Tries***

| Group number | Person | Lathe Experience | Part1 | Part 2 | Part 3 | Part 4 | Part 5 | Part 6 | Part 7 | Part 8 | Part 9 | Sum | Avg |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 1 | N | 1 | 3 | 1 | 1 | 1 | 1 | 1 | 2 | 1 | 12 | **10.8** |
| 1 | 2 | Y | 1 | 1 | 2 | 1 | 2 | 3 | 1 | 1 | 1 | 12 | |
| 1 | 3 | Y | 1 | 1 | 1 | 1 | 1 | 1 | 2 | 1 | 1 | 10 | |
| 1 | 4 | N | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 9 | |
| 1 | 5 | N | 1 | 2 | 1 | 1 | 1 | 2 | 1 | 1 | 1 | 11 | |
| 2 | 6 | N | 4 | 2 | 1 | 3 | 3 | 1 | 2 | 1 | 1 | 18 | **18.33** |
| 2 | 7 | N | 1 | 3 | 1 | 1 | 3 | 3 | 1 | 1 | 1 | 15 | |
| 2 | 8 | Y | 1 | 1 | 1 | 1 | 2 | 1 | 1 | 1 | 1 | 10 | |
| 2 | 9 | Y | 1 | 3 | 1 | 1 | 4 | 3 | 1 | 1 | 2 | 17 | |
| 2 | 10 | N | 2 | 2 | 1 | 1 | 1 | 3 | 3 | 1 | 3 | 17 | |
| 2 | 11 | N | 1 | 1 | 4 | 1 | 5 | 5 | 3 | 5 | 5 | 33 | |
| 3 | 12 | N | 5 | 1 | 1 | 1 | 4 | 2 | 1 | 1 | 1 | 17 | **21.75** |
| 3 | 13 | N | 3 | 5 | 1 | 1 | 2 | 4 | 2 | 1 | 1 | 20 | |
| 3 | 14 | N | 6 | 4 | 1 | 1 | 10 | 1 | 1 | 1 | 1 | 26 | |
| 3 | 15 | N | 1 | 3 | 1 | 10 | 4 | 1 | 1 | 1 | 2 | 24 | |

***Duration (seconds)***

| Group number | Person | Lathe Experience | Part1 | Part 2 | Part 3 | Part 4 | Part 5 | Part 6 | Part 7 | Part 8 | Part 9 | Sum | Avg |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 1 | N | 6 | 50 | 12 | 5 | 16 | 15 | 26.56 | 12 | 3 | 145.56 | **123.32** |
| 1 | 2 | Y | 5.5 | 7.09 | 6.5 | 2 | 7.9 | 20 | 19.52 | 3.6 | 15 | 67.59 | |
| 1 | 3 | Y | 5 | 4.2 | 4.69 | 3.14 | 6.07 | 15.02 | 12.55 | 8.59 | 6.2 | 65.46 | |
| 1 | 4 | N | 8 | 12.57 | 11.9 | 13.79 | 25.23 | 23.35 | 26.49 | 12.51 | 9.03 | 142.87 | |
| 1 | 5 | N | 9.16 | 17 | 7.93 | 2 | 15.55 | 44.37 | 40.63 | 9.17 | 49.33 | 195.14 | |
| 2 | 6 | N | 36 | 54 | 22 | 33 | 30 | 23 | 22 | 25 | 11 | 256.00 | **244.08** |
| 2 | 7 | N | 26.44 | 67.8 | 7.58 | 5.31 | 69.58 | 85.9 | 21.54 | 6.38 | 8.75 | 299.28 | |
| 2 | 8 | Y | 6.29 | 5.34 | 3.45 | 4.35 | 31.38 | 6.53 | 7.22 | 5.51 | 5.4 | 75.47 | |
| 2 | 9 | Y | 12 | 34 | 8 | 2 | 80 | 50 | 30 | 11.30 | 27.72 | 255.01 | |
| 2 | 10 | N | 27 | 11 | 5 | 3 | 16 | 48 | 66 | 22 | 69 | 267.00 | |
| 2 | 11 | N | 7.88 | 10 | 32.12 | 2 | 58.53 | 60 | 51.67 | 74.52 | 15 | 311.72 | |
| 3 | 12 | N | 75 | 17 | 15 | 15 | 55 | 50 | 22 | 20 | 11 | 280.00 | **257.67** |
| 3 | 13 | N | 11.65 | 46.12 | 9.35 | 6.62 | 63.64 | 61.017 | 14.39 | 6.97 | 19.71 | 239.47 | |
| 3 | 14 | N | 2.08 | 73.28 | 9.99 | 10.11 | 144.35 | 18.72 | 14.32 | 5.19 | 8.94 | 286.98 | |
| 3 | 15 | N | 10.59 | 38.58 | 7.38 | 68.86 | 50.35 | 8.81 | 14.56 | 10.54 | 14.56 | 224.23 | |

| Legend |
|---|
| Data was interpolated from group avg. |
| Person did not pass the test (stop after at 10 tries) |

Table E.2: Mean and Standard Deviations for Different Groups with and without Experience for Machine Shop Testing

| | All Samples | | | | Samples with Experience Removed | | | |
|---|---|---|---|---|---|---|---|---|
| | Mean No. Tries | SD | Mean Duration (secs) | SD | Mean No. Tries | SD | Mean Duration (secs) | SD |
| **Group 1** | 10.8 | 1.3 | 123.3 | 55.9 | 10.7 | 1.5 | 163.5 | 27.8 |
| **Group 2** | 18.3 | 7.7 | 244.1 | 85.8 | 20.8 | 8.3 | 283.5 | 26.3 |
| **Group 3** | 21.8 | 4.0 | 257.7 | 30.6 | 21.8 | 4.0 | 257.7 | 30.6 |

# Appendix F Views for Different Testing Groups

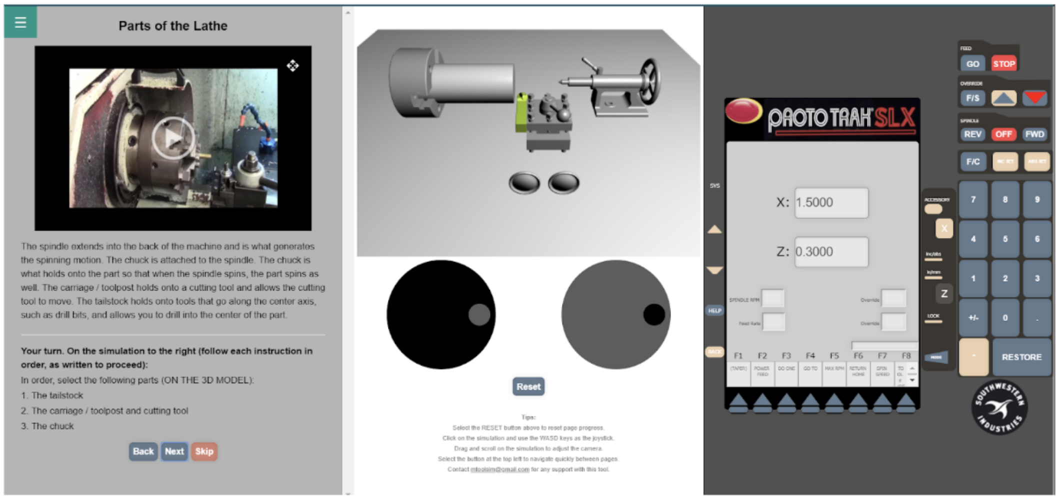



Figure F.1: Group 1 (MTS) View

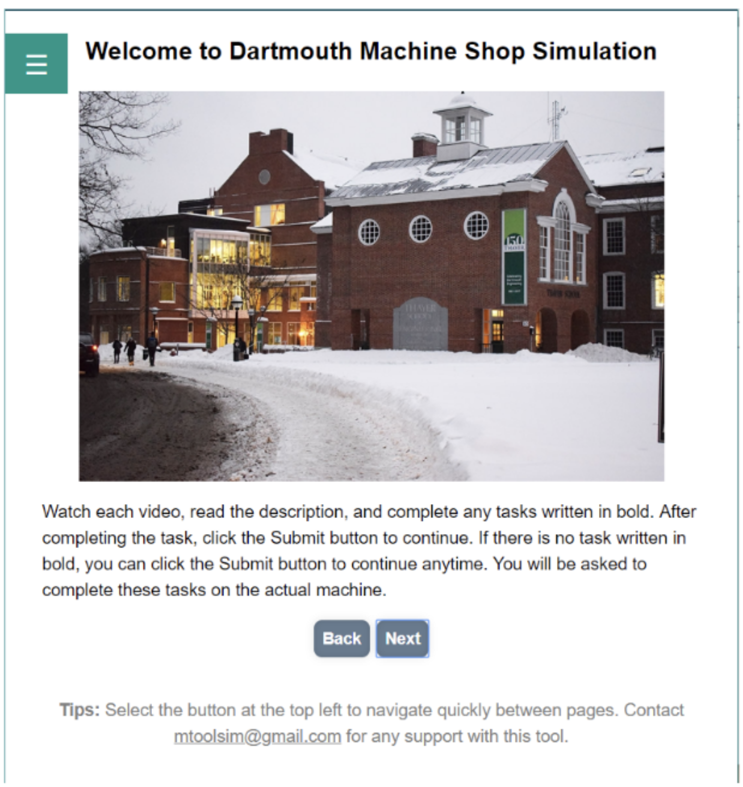



Figure F.2: Group 2 (Video-only) View

# Appendix G Machine Shop Test Sheets

The following is the test sheet that was used to record data from for Engs 90 testing:

**DARTMOUTH MACHINE SHOP / ENGS 21 LATHE EVALUATION / ENGS 89 GROUP 15**

→ *Scan, upload, and input data when complete. If lost, email to mtoolsim@gmail.com* ←

**INFORMATION**

| Student | Timing | Test |
|---|---|---|
| Name: ________ | Start time: ________ | Date: ________ |
| Identification No: ________ | End time: ________ | Evaluator 1: ________ |
| Engs 21 Group No: ________ | Duration: ________ | Evaluator 2: ________ |

**SKILL CHECKS**

***NOTE:*** *Always mark whether task actually complete; max duration at 1 minute to accommodate others.*

**1. Statement:** In order, identify the **tailstock**, the **carriage** (cutting tool), and then the **chuck**.

Checklist:

[ ] Identifies **tailstock**
[ ] Identifies **carriage** (cutting tool)
[ ] Identifies **chuck**

Completed successfully? Y / N

No Tries (1 if only 1): ________

Duration: ________

(Start: ________ / End: ________)

**2. Statement:** **Turn on** the spindle. Then **turn off** the spindle.

Checklist:

[ ] Presses **"FWD"**
[ ] Presses **"OFF"**

Completed successfully? Y / N

No Tries (1 if only 1): ________

Duration: ________

(Start: ________ / End: ________)

**3. Statement:** Set spindle speed to a **Constant RPM** of 500. Turn on and off the spindle.

Checklist:

[ ] Selects "Spin Speed"
[ ] Enters "500" using the keypad
[ ] Presses **"Inc Set"** to set constant RPM
[ ] Turns on the spindle
[ ] Turns off the spindle

Completed successfully? Y / N

No Tries (1 if only 1): ________

Duration: ________

(Start: ________ / End: ________)

**4. Statement:** Set spindle speed to a **Constant SFM** of 250. Turn on and off the spindle

Checklist:

[ ] Selects "Spin Speed"
[ ] Enters "250" using the keypad
[ ] Presses **"Abs Set"** to set constant SFM
[ ] Turns on the spindle
[ ] Turns off the spindle

Completed successfully? Y / N

No Tries (1 if only 1): ________

Duration: ________

(Start: ________ / End: ________)

**DARTMOUTH MACHINE SHOP / ENGS 21 LATHE EVALUATION / ENGS 89 GROUP 15**

**5. Statement:** Move cutting tool / carriage to a position of (state position that would be reasonable).

Checklist:

[ ] Uses **X wheel** to appropriately move tool to the position
[ ] Uses **Z wheel** to appropriately move tool to the position

Completed successfully? Y / N

No Tries (1 if only 1): ___________

Duration: _____________________

(Start: ________ / End: ________)

**6. Statement:** Turn the spindle from **Fine** to **Coarse** control, then back to **Fine** control.

Checklist:

[ ] Sets the lathe from **"Coarse"** control to **"Fine"** control
[ ] Sets the lathe from **"Fine"** control to **"Coarse"** control

Completed successfully? Y / N

No Tries (1 if only 1): ___________

Duration: _____________________

(Start: ________ / End: ________)

**7. Statement:** Move the cutting tool to a new position near the material and set the z coordinate to 0.

Checklist:

[ ] Moves cutting tool to a new position near the material
[ ] Sets z coordinate to 0

Completed successfully? Y / N

No Tries (1 if only 1): ___________

Duration: _____________________

(Start: ________ / End: ________)

**8. Statement:** Using **calipers**, measure the size of the material and set the x coordinate appropriately.

Checklist:

[ ] Given calipers and user understands how they work
[ ] Successfully measures diameter of material with calipers
[ ] Sets the x coordinate value to the measurement

*(This is a good test of understanding from videos to lathe)*

Completed successfully? Y / N

No Tries (1 if only 1): ___________

Duration: _____________________

(Start: ________ / End: ________)

**9. Statement:** Set the lathe to a **"Go To"** position of **3** in the **X-direction** and **3** in the **Z-direction**.

Checklist:

[ ] Selects **"Go To"** function
[ ] Presses **"X"** button
[ ] Enters **"3"** using keypad
[ ] Presses **"Abs Set"** to set value
[ ] Presses **"Z"** button
[ ] Enters **"3"** using keypad
[ ] Presses **"Abs Set"** to set value
[ ] Exits "Go To" by selecting **"Return"**

Completed successfully? Y / N

No Tries (1 if only 1): ___________

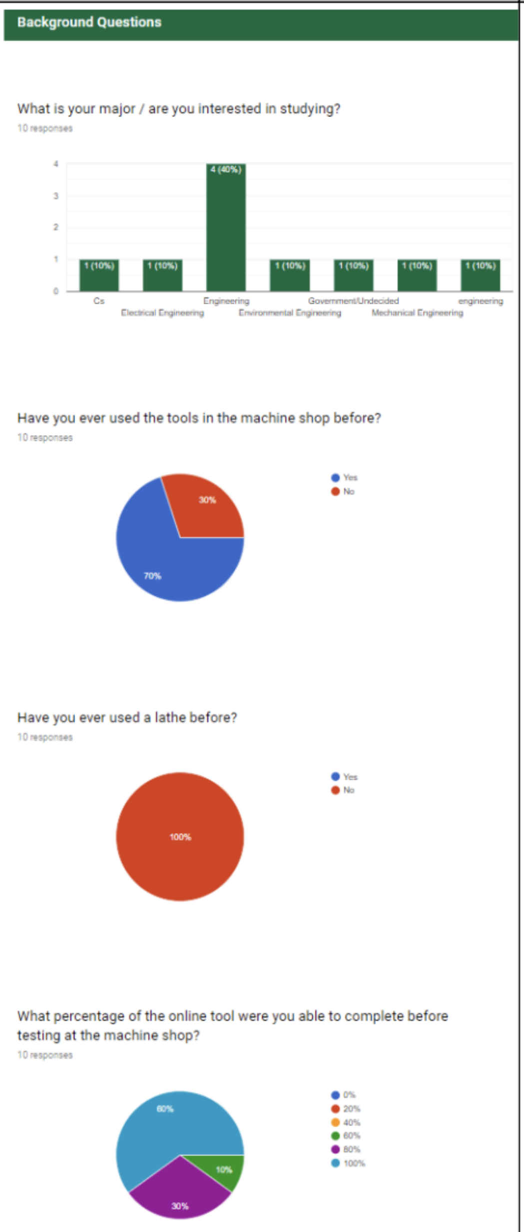
Duration: _____________________

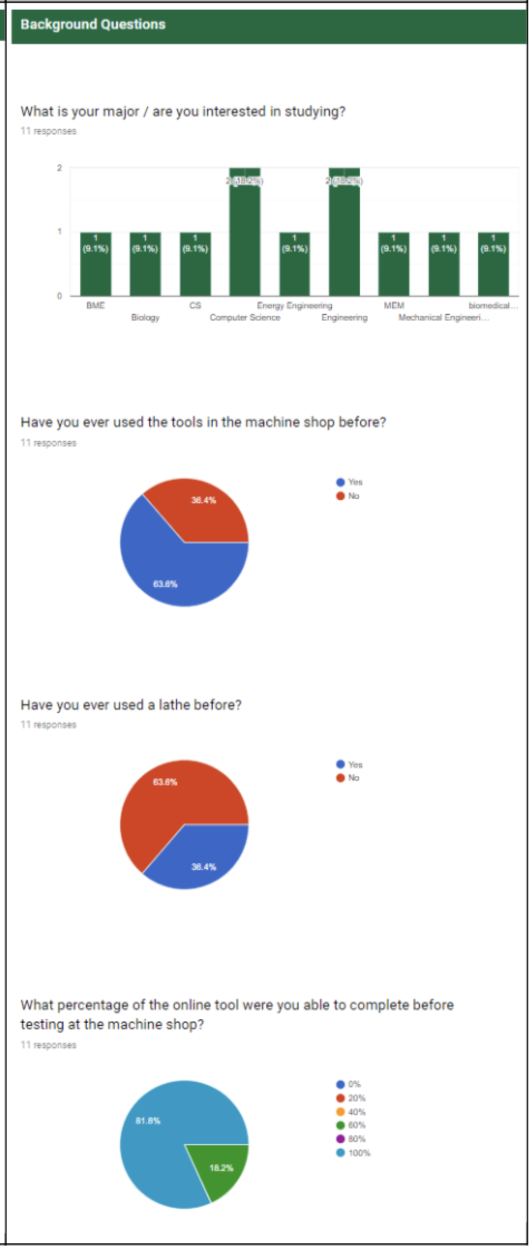
(Start: ________ / End: ________)

**Time finished / duration: _________ | No Tries (1 if only 1): _________ | Successful skills: _______**

# Appendix H Volunteer Background

Table H.1: Information on the background of the test users

<table>
<tr><th>Group 1 (MTS and videos)</th><th>Group 2 (videos only)</th></tr>
<tr><td>


</td><td>


</td></tr>
</table>

# Appendix I Raw Data Results from ENGS 90

Table I.1: Engs 90 testing number of tries to complete tasks

| ID number | Group number | Name | Part1 | Part 2 | Part 3 | Part 4 | Part 5 | # Tries<br>Part 6 | Part 7 | Part 8 | Part 9 | Sum | Avg | SD |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 2 (used # 0 though) | 0 | Jason Liu | 1 | 1 | 3 | 1 | 1 | 1 | 1 | 2 | 2 | 13 | 10.33 | 1.50 |
| 39 | 0 | Kieran Ahern | 2 | 1 | 1 | 1 | 1 | 1 | 1 | 2 | 1 | 11 | | |
| 18 | 0 | Cara | 2 | 1 | 2 | 1 | 1 | 1 | 1 | 1 | 2 | 12 | | |
| 24 | 0 | Matt | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 9 | | |
| 12 | 0 | Elizabeth | 1 | 1 | 2 | 1 | 1 | 1 | 1 | 1 | 1 | 10 | | |
| 42 | 0 | Michelle Wang | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 9 | | |
| 0 | 0 | Namya Malik | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 9 | | |
| 36 | 0 | Abigail Brazil | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 9 | | |
| 48 | 0 | Angeline Janumala | 1 | 1 | 2 | 1 | 1 | 1 | 1 | 2 | 1 | 11 | | |
| | | AVERAGES | 1.22 | 1.00 | 1.56 | 1.00 | 1.00 | 1.00 | 1.00 | 1.33 | 1.22 | | | |
| 14 | 2 | Lindsey | 1 | 1 | 2 | 1 | 1 | 1 | 1 | 1 | 1 | 10 | 13.91 | 3.21 |
| 20 | 2 | Rajiv | 2 | 4 | 1 | 4 | 1 | 1 | 1 | 2 | 1 | 17 | | |
| 5 | 2 | Jane Lee | 2 | 1 | 1 | 1 | 1 | 2 | 1 | 1 | 1 | 11 | | |
| 8 | 2 | Francesco | 2 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 10 | | |
| 11 | 2 | Soon Young Shimizu | 1 | 1 | 2 | 2 | 1 | 1 | 2 | 1 | 1 | 12 | | |
| 29 | 2 | Jessie | 2 | 2 | 4 | 1 | 1 | 5 | 1 | 2 | 2 | 20 | | |
| 47 | 2 | Yaqi Li | 1 | 1 | 2 | 2 | 1 | 1 | 1 | 2 | 1 | 12 | | |
| 26 | 2 | Zheer Xu | 2 | 3 | 2 | 1 | 1 | 3 | 2 | 1 | 1 | 16 | | |
| 44 | 2 | Sam Greenberg | 1 | 1 | 2 | 1 | 1 | 2 | 3 | 2 | 1 | 14 | | |
| 50 | 2 | Garret | 1 | 1 | 4 | 1 | 1 | 1 | 1 | 2 | 4 | 16 | | |
| | 2 | Julian | 2 | 1 | 5 | 1 | 1 | 1 | 1 | 1 | 2 | 15 | | |
| | | AVERAGES | 1.55 | 1.55 | 2.36 | 1.45 | 1.00 | 1.73 | 1.36 | 1.45 | 1.45 | | | |
| INCOMPLETE | | | | | | | | | | | | | | |
| | | Video-only - MTS | -0.32 | -0.55 | -0.81 | -0.45 | 0.00 | -0.73 | -0.36 | -0.12 | -0.23 | 0.00 | 0.00 | 0.00 |

Table I.2: Engs 90 testing duration to complete tasks

| ID number | Group number | Name | Part1 | Part 2 | Part 3 | Part 4 | Duration<br>Part 5 | (seconds)<br>Part 6 | Part 7 | Part 8 | Part 9 | Sum | Avg | SD |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 2 (used # 0 though) | 0 | Jason Liu | 12.45 | 5.64 | 43.87 | 15.77 | 35.34 | 8.23 | 52.95 | 87.72 | 27.23 | 289.20 | 202.77 | 65.97 |
| 39 | 0 | Kieran Ahern | 33.87 | 9.56 | 20.31 | 17.98 | 52.98 | 8.54 | 35.69 | 61.03 | 19.37 | 259.33 | | |
| 18 | 0 | Cara | 11 | 3.52 | 19 | 6 | 5 | 4 | 13.00 | 25 | 29 | 115.52 | | |
| 24 | 0 | Matt | 9.41 | 15.07 | 29.15 | 17.97 | 34.08 | 7.28 | 33.21 | 35.94 | 18.34 | 200.45 | | |
| 12 | 0 | Elizabeth | 19.63 | 3.05 | 29.04 | 6.91 | 18.34 | 3.01 | 5.31 | 45.63 | 10.37 | 141.29 | | |
| 42 | 0 | Michelle Wang | 12 | 11 | 30 | 15 | 38 | 16 | 28.00 | 48 | 40 | 238.00 | | |
| 0 | 0 | Namya Malik | 13 | 5 | 9 | 5 | 39 | 5 | 37 | 34 | 9 | 156.00 | | |
| 36 | 0 | Abigail Brazil | 15.06 | 7.13 | 18.21 | 4.03 | 26.34 | 3 | 26.99 | 22.8 | 21.46 | 145.02 | | |
| 48 | 0 | Angeline Janumala | 13.1 | 8.05 | 34 | 13.13 | 42.98 | 7.69 | 31.7 | 120 | 9.51 | 280.16 | | |
| | | AVERAGES | 15.50 | 7.56 | 25.84 | 11.31 | 32.45 | 6.97 | 29.32 | 53.35 | 20.48 | | | |
| 14 | 2 | Lindsey | 23 | 7 | 40 | 5 | 7.5 | 15 | 48.00 | 65 | 20 | 230.50 | 290.69 | 102.36 |
| 20 | 2 | Rajiv | 15 | 83 | 23 | 68 | 17 | 7 | 30.00 | 82 | 39 | 364.00 | | |
| 5 | 2 | Jane Lee | 52.99 | 24.71 | 53.22 | 7.06 | 68 | 35.01 | 84.2 | 134 | 63 | 522.19 | | |
| 8 | 2 | Francesco | 10 | 12 | 20 | 25 | 30 | 5 | 10 | 40 | 50 | 202.00 | | |
| 11 | 2 | Soon Young Shimizu | 8 | 10 | 32 | 46 | 22 | 5 | 34 | 40 | 15 | 212.00 | | |
| 29 | 2 | Jessie | 48 | 25 | 38 | 7 | 20 | 54 | 23 | 39 | GIVE UP | 254.00 | | |
| 47 | 2 | Yaqi Li | 21 | 10 | 28 | 46 | 38 | 9 | 60 | 105 | 40 | 357.00 | | |
| 26 | 2 | Zheer Xu | 25 | 40 | 30 | 62 | 53 | 52 | 48 | 28 | 42 | 380.00 | | |
| 44 | 2 | Sam Greenberg | 22.13 | 8.77 | 27.59 | 16.7 | 42.69 | 24.74 | 39.79 | 35.54 | 24.65 | 242.60 | | |
| 50 | 2 | Garret | 3 | 4.2 | 57.6 | 7.46 | 6.2 | 4.82 | 47.3 | 7.3 | 54.98 | 192.86 | | |
| | 2 | Julian | 27 | 9 | 85.66 | 10 | 9 | 5.26 | 25 | 37.16 | 32.31 | 240.39 | | |
| | | AVERAGES | 23.21 | 22.67 | 39.51 | 29.52 | 30.59 | 20.18 | 40.13 | 54.80 | 40.10 | | | |
| INCOMPLETE | | | | | | | | | | | | | | |
| | | Video-only - MTS | -7.71 | -15.11 | -13.66 | -18.21 | 1.86 | -13.21 | -10.81 | -1.45 | -19.63 | | | |

# Appendix J Additional Data Analysis Figures and Tables for ENGS 90

Note: Titles in this section correspond to those in subsection II.4.

## J.1 Testing Procedure

Table J.1: The modifications in the in-shop testing

| **Only in old** | **Only in new** |
|---|---|
| Part 6 in old | Part 1 in new |
| Part 7 in old | Part 5 in new |
| Part 8 in old | Part 7 in new |
| Part 9 in old | Part 8 in new ("Calipers") |

## J.2 Outlier Test

Table J.2: Grubbs' Test for Outlier

**Grubbs' Test**

| Variable | N | Mean | StDev | Min | Max | G | P |
|---|---|---|---|---|---|---|---|
| MTS numb_tries | 10 | 11.100 | 2.807 | 9.000 | 18.000 | 2.46 | 0.013 |
| Video numb_tries | 11 | 13.909 | 3.208 | 10.000 | 20.000 | 1.90 | 0.416 |
| MTS total_time | 10 | 213.6 | 84.5 | 108.5 | 370.5 | 1.86 | 0.411 |
| Video total_time | 11 | 290.7 | 102.4 | 192.9 | 522.2 | 2.26 | 0.086 |

Table J.3: Outlier Test Indicator

**Outlier**

| Variable | Row | Outlier |
|---|---|---|
| MTS numb_tries | 9 | 18 |

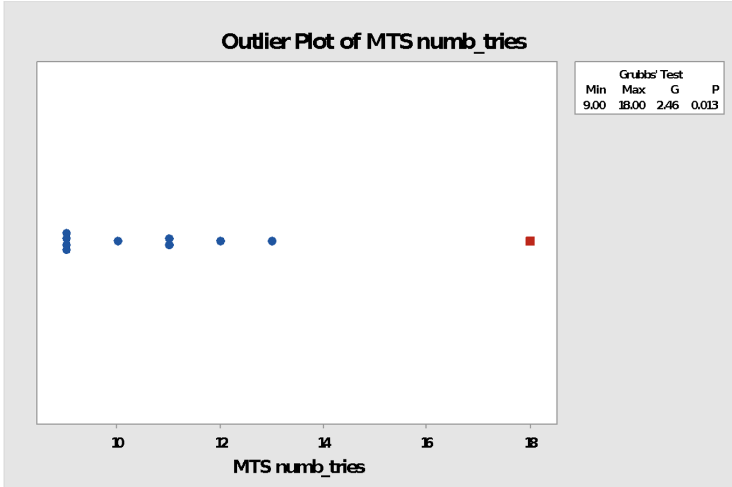



Figure J.1: Outlier Plot (note the red dot for the outlier)

## J.3 T-tests

### Two-Sample T-Test and CI: MTS numb_tries, Video numb_tries

#### Method

$\mu_1$: mean of MTS numb_tries
$\mu_2$: mean of Video numb_tries
Difference: $\mu_1 - \mu_2$

*Equal variances are not assumed for this analysis.*

#### Descriptive Statistics

| Sample | N | Mean | StDev | SE Mean |
|---|---|---|---|---|
| MTS numb_tries | 9 | 10.33 | 1.50 | 0.50 |
| Video numb_tries | 11 | 13.91 | 3.21 | 0.97 |

#### Estimation for Difference

| Difference | 95% CI for Difference |
|---|---|
| -3.58 | (-5.91, -1.24) |

#### Test

Null hypothesis $H_0: \mu_1 - \mu_2 = 0$
Alternative hypothesis $H_1: \mu_1 - \mu_2 \neq 0$

| T-Value | DF | P-Value |
|---|---|---|
| -3.28 | 14 | 0.005 |

Figure J.2: T-test number of tries to complete tasks on actual lathe

### Two-Sample T-Test and CI: MTS total_time, Video total_time

#### Method

$\mu_1$: mean of MTS total_time
$\mu_2$: mean of Video total_time
Difference: $\mu_1 - \mu_2$

*Equal variances are not assumed for this analysis.*

#### Descriptive Statistics

| Sample | N | Mean | StDev | SE Mean |
|---|---|---|---|---|
| MTS total_time | 9 | 196.2 | 68.0 | 23 |
| Video total_time | 11 | 291 | 102 | 31 |

#### Estimation for Difference

| Difference | 95% CI for Difference |
|---|---|
| -94.5 | (-175.3, -13.7) |

#### Test

Null hypothesis $H_0: \mu_1 - \mu_2 = 0$
Alternative hypothesis $H_1: \mu_1 - \mu_2 \neq 0$

| T-Value | DF | P-Value |
|---|---|---|
| -2.47 | 17 | 0.025 |

Figure J.3: T-test time taken to complete tasks on actual lathe

## J.4 Other Details

Table J.4: Number of tries (MTS - Video-only) from most recent tests (Engs 90)

| Part Number | MTS - Video-only (avg. #) |
|---|---|
| 1 | -0. |
| 2 | -0.55 |
| 3 | -0.86 |
| 4 | -0.25 |
| 5 | 0.00 |
| 6 | -0.73 |
| 7 | -0.06 |
| 8 | -0.05 |
| 9 | -0.25 |

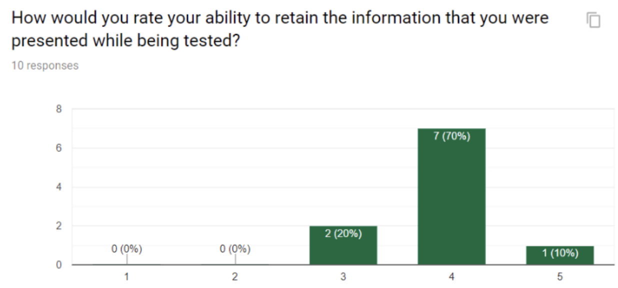
Table J.5: Time taken (MTS - Video-only) from most recent tests (Engs 90)

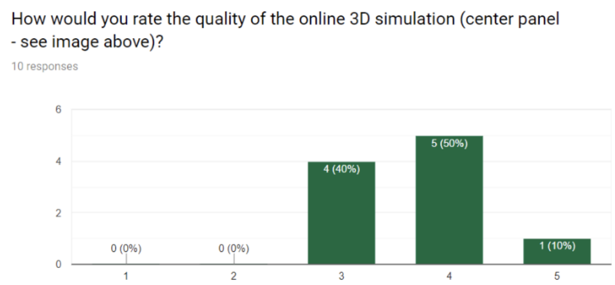
| Part Number | MTS - Video-onl (avg. secs) |
|---|---|
| 1 | 0.14 |
| 2 | -15.15 |
| 3 | -14.07 |
| 4 | -11.72 |
| 5 | 0.70 |
| 6 | -11.72 |
| 7 | -4.53 |
| 8 | 6.24 |
| 9 | -20.56 |

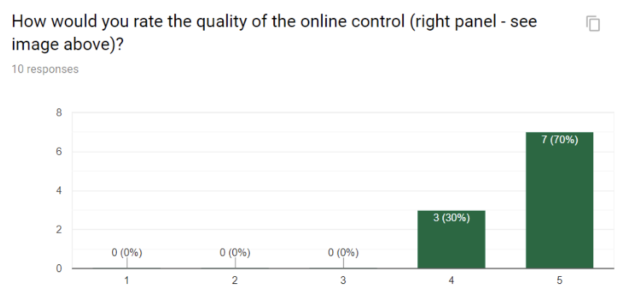
# Appendix K Detailed Survey Results

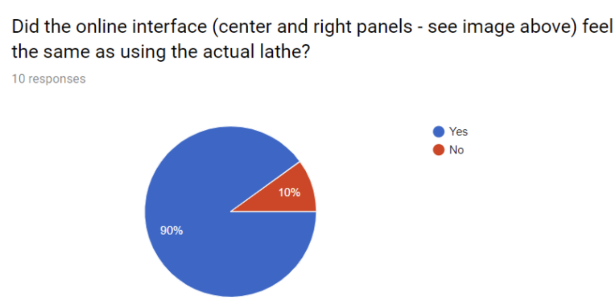
## K.1 Figures and Tables

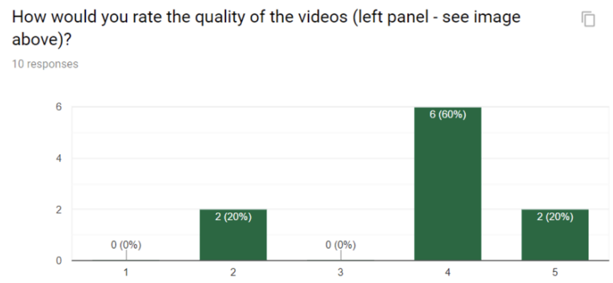
### K.1.A Group 1 (MTS)

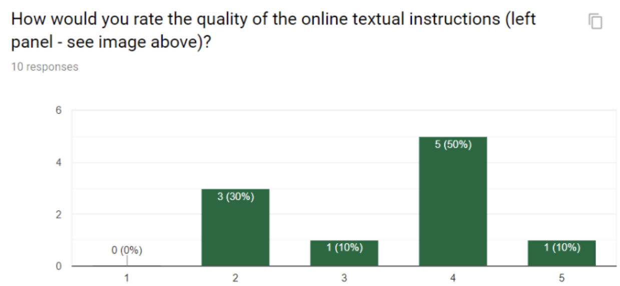


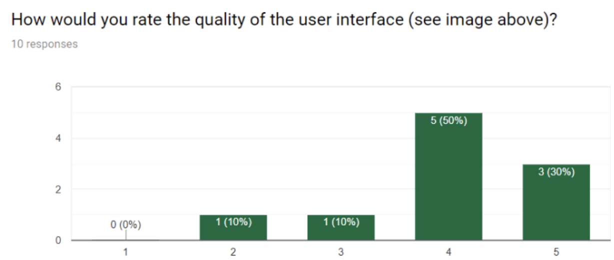



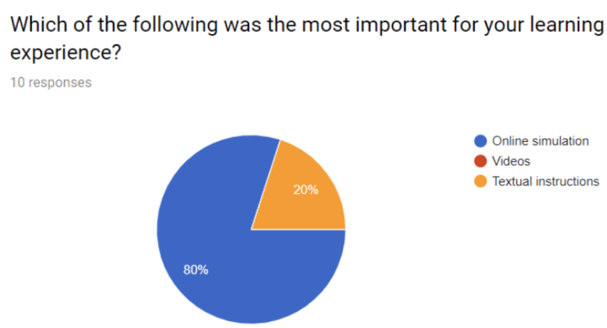




How would you rate the quality of the videos (left panel - see image above)?
10 responses
0 (0%)
2 (20%)
0 (0%)
6 (60%)
2 (20%)

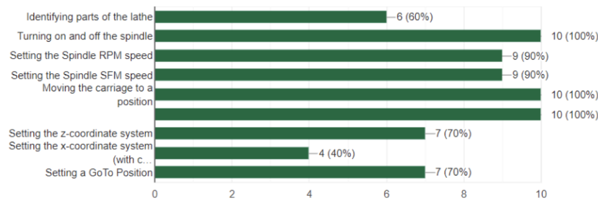

How would you rate the quality of the online textual instructions (left panel - see image above)?
10 responses
0 (0%)
3 (30%)
1 (10%)
5 (50%)
1 (10%)


How would you rate the quality of the user interface (see image above)?
10 responses
0 (0%)
1 (10%)
1 (10%)
5 (50%)
3 (30%)


Which of the following was the most important for your learning experience?
10 responses
Online simulation
Videos
Textual instructions
20%
80%

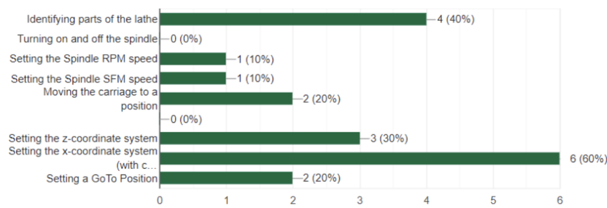
Which of the following skills did you feel comfortable performing in the machine shop?

10 responses




Which of the following skills did you NOT feel comfortable performing in the machine shop?

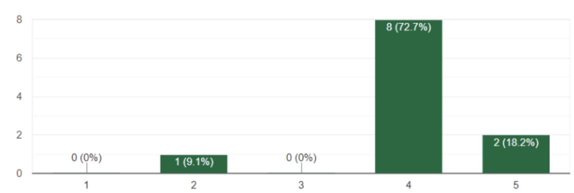
10 responses




### K.1.B Group 2 (Video-only)

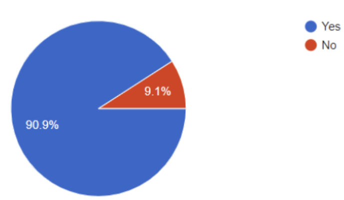
How would you rate your ability to retain the information that you were presented while being tested?

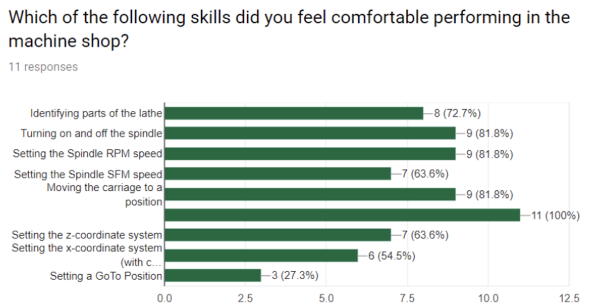
11 responses

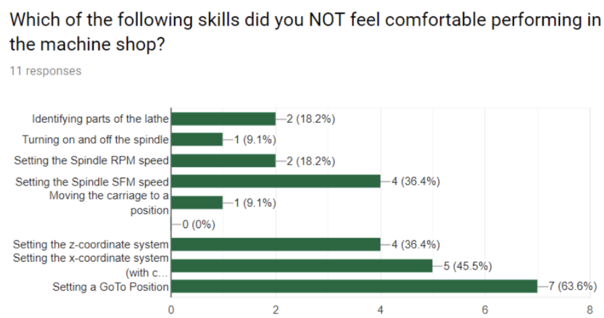



Would you have liked to have interacted with a simulation of the tool before being tested?

11 responses






## K.2 Select Qualitative Written Feedback

- "The tutorial was very helpful-I especially enjoyed the video and then immediate practicing of what we learned with the online simulation."
- "I thought it was pretty practical and easy to use but I think it would be helpful if there was a short multiple choice quiz after each informative slide just to reiterate what I watched in the video."
- "If you click on a part of the lathe in the simulator, it should become a different color to indicate that it has been clicked. Also should probably allow use of the arrow keys to turn the dials instead of swinging the mouse around, very annoying on a touchpad."
- "Maybe simulate how things can go wrong on the lathe to warn against them."
- "I thought it was very helpful overall and I appreciated the shorter videos as opposed to one long video as for the mill."

# Appendix L Timing per page / Instruction Breakdown

Table L.1: Timing per online instruction page

| ID | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | Timestamp | Sum (secs) | Sum (minutes) | Average | Stdev |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 12 | 28 | 3 | 1 | 76 | 61 | 26 | 126 | 53 | 7 | 32 | 26 | 80 | 607 | 615 | 58 | 0 | Wed Jan 23 2019 21:19:11 GMT-0500 (Eastern Standard Time) | 1799 | 29.98 | 30.08 | 6.65 |
| 24 | 43 | 274 | 100 | 107 | 46 | 36 | 55 | 49 | 56 | 146 | 101 | 275 | 268 | 488 | 163 | 0 | Thu Jan 24 2019 00:19:05 GMT-0500 (Eastern Standard Time) | 2207 | 36.78 | | |
| 42 | 20 | 161 | 19 | 149 | 10 | 41 | 74 | 24 | 33 | 30 | 93 | 160 | 128 | 304 | 163 | 0 | Thu Jan 24 2019 23:55:47 GMT-0500 (Eastern Standard Time) | 1409 | 23.48 | | |
| 9 | 40 | 134 | 20 | 382 | 3 | 24 | 35 | 23 | 2 | 64 | 8 | 94 | 6 | 3 | 9 | 0 | Thu Jan 24 2019 00:37:55 GMT-0500 (Eastern Standard Time) | 847 | 14.12 | * | * |

(Note, it appears that the user with ID 9 became frustrated after page 4 and skipped past pages. Thus, this data point was not included in the final calculation, since it is an outlier.)

**Instructions on each page:**

- Introduction
- Timelapse
- Safety
- Parts of the Lathe
- Loading the Chuck
- Turning on the Spindle
- Constant RPM
- Constant SFM
- X and Z Coordinate System
- X and Z Wheels
- Fine and Coarse Control
- Cutting and Setting Z Coordinate System
- Setting X Coordinate System
- Setting a GoTo Position

# Appendix M How Prototype Meets Requirements Details

Table M.1: Timing per online instruction page

| | |
|---|---|
| *1. Reduces time to instruct students by at least 10 minutes; as a reach, reduces by 20 minutes*<br>**Yes** - The time it took students to complete the online instruction tool was approximately 30 minutes. If only a fraction of this time was saved in the machine shop, when other skills are added for the lathe, this requirement will be met. | *2. The software opens the possibility for more skills to be taught in the machine shop*<br>**Yes** - The product teaches many of the skills that were taught in the shop. Assuming that the online instruction tool helps alleviate any of the time to teach the students, this requirement has been met because instructors will now have more time to each more. |
| *3. Record number of skills taught before and after software use*<br>**Yes** - From the online tool with simulation, students were able to learn the same skills that were provided by our sponsor as necessary to use the lathe. | *4. Students rate on a survey that they are comfortable with skills more than 80% of the time*<br>**Yes** – Based on the survey answered by the students, over 80% of the students felt comfortable performing the skills that were tested in the machine shop. |
| *5. Students meet 95% of the learning goals for the shop*<br>**Yes** - Students were able to demonstrate that the skills that we selected for learning the control in greater than 95% of cases. | *6. Software is available >20 hours / day*<br>**Yes** - The software is on a website platform which is hosted by Github. This webpage was always up whenever it has been checked (it has been up ~24/7). |
| *7. Software is accessible in each of the places that we test*<br>**Yes** - Software has been tested by a variety of students who live in different locations both on campus and off campus. They have all been able to access the provided software. It can even be accessed on mobile. | *8. Compatible with Windows, Mac, and Linux*<br>**Yes** - The software is compatible with all the operating systems that have access to a web browser. It is also compatible with iOS and Android web browsers. |
| *9. Compatible with Chrome, Firefox, and Safari*<br>**Yes** - The software has been tested on each of these browsers and is compatible with each of them. It is also compatible with mobile web browsers. | *10. The code is modularized and a workflow and framework are developed for applying to other machines*<br>**Yes** - New skills can be added by adding additional code to the JSON file. |
| *11. Documentation is provided for main components: instruction, evaluation, scaling*<br>**No** - Documentation has been incorporated as a *readme.md* file that can be viewed on Github. | *12. A third-party reviews our repository and confirms they understand each component*<br>**Yes** – The sponsor, Nick, has been raising issues on GitHub that have been addressed. |
| *13. All software bugs raised have been carefully handled*<br>**Yes** - In addition to the primary issues raised by our sponsor, all of the most important issues raised by our testers in the survey results have been addressed. | *14. All tasks must be completed before finishing the teaching tool*<br>**Yes** - Users will not be allowed to move to the next task until they master the previous skill and pass the test. If the skip button is used, this could be logged. |

# Appendix N Thayer Machine Shop TA Employee Record

Table N.1: Thayer Machine Shop TA log data (used for section IV

**Thayer School of Engineering**

**Recorded Employee Activity Summary**

Date Range: 1/1/2018 to 12/31/2018

Filter: (Employee Has Activities Is true) AND (Position Is Shop TA level 1)

Sort Order: Employee Name Ascending

*Work hours in this report are calculated from punch records. A question mark (?) indicates that a shift has not been punched out.*

| | | | Work | Work Hours | | | On Call | | Time Off Hours | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Employee | Home Location | Position | Shifts | Regular | Overtime | Total | Shifts | Hours | Payable | No-Pay | |
| | shop floor | Shop TA level 1 | 71 | 538.42 | 0.00 | 538.42 | 0 | 0.00 | 0.00 | 0.00 | ? |
| | Machine Shop | Shop TA level 1 | 52 | 374.08 | 0.00 | 374.08 | 0 | 0.00 | 0.00 | 0.00 | |
| | Machine Shop | Shop TA level 1 | 29 | 72.53 | 0.00 | 72.53 | 0 | 0.00 | 0.00 | 0.00 | ? |
| | Machine Shop | Shop TA level 1 | 23 | 57.05 | 0.00 | 57.05 | 0 | 0.00 | 0.00 | 0.00 | ? |
| | Machine Shop | Shop TA level 1 | 82 | 488.88 | 0.00 | 488.88 | 0 | 0.00 | 0.00 | 0.00 | ? |
| | Machine Shop | Shop TA level 1 | 19 | 37.70 | 0.00 | 37.70 | 0 | 0.00 | 0.00 | 0.00 | ? |
| | Machine Shop | Shop TA level 1 | 20 | 114.23 | 0.00 | 114.23 | 0 | 0.00 | 0.00 | 0.00 | ? |
| | Machine Shop | Shop TA level 1 | 44 | 294.52 | 0.00 | 294.52 | 0 | 0.00 | 0.00 | 0.00 | ? |
| | Machine Shop | Shop TA level 1 | 53 | 346.92 | 0.00 | 346.92 | 0 | 0.00 | 0.00 | 0.00 | |
| | Machine Shop | Shop TA level 1 | 53 | 216.62 | 0.00 | 216.62 | 0 | 0.00 | 0.00 | 0.00 | |
| | Machine Shop | Shop TA level 1 | 44 | 298.90 | 0.00 | 298.90 | 0 | 0.00 | 0.00 | 0.00 | ? |
| | Machine Shop | Shop TA level 1 | 20 | 122.90 | 0.00 | 122.90 | 0 | 0.00 | 0.00 | 0.00 | ? |
| | Machine Shop | Shop TA level 1 | 23 | 54.25 | 0.00 | 54.25 | 0 | 0.00 | 0.00 | 0.00 | ? |
| | Machine Shop | Shop TA level 1 | 12 | 91.73 | 0.00 | 91.73 | 0 | 0.00 | 0.00 | 0.00 | |
| | Machine Shop | Shop TA level 1 | 78 | 216.05 | 0.00 | 216.05 | 0 | 0.00 | 0.00 | 0.00 | ? |
| | Machine Shop | Shop TA level 1 | 21 | 48.85 | 0.00 | 48.85 | 0 | 0.00 | 0.00 | 0.00 | ? |
| | shop floor | Shop TA level 1 | 1 | 1.25 | 0.00 | 1.25 | 0 | 0.00 | 0.00 | 0.00 | |
| | Machine Shop | Shop TA level 1 | 41 | 270.35 | 0.00 | 270.35 | 0 | 0.00 | 0.00 | 0.00 | ? |
| | shop floor | Shop TA level 1 | 49 | 209.60 | 0.00 | 209.60 | 0 | 0.00 | 0.00 | 0.00 | |
| | shop floor | Shop TA level 1 | 24 | 114.52 | 0.00 | 114.52 | 0 | 0.00 | 0.00 | 0.00 | ? |
| | Machine Shop | Shop TA level 1 | 41 | 160.28 | 0.00 | 160.28 | 0 | 0.00 | 0.00 | 0.00 | ? |
| | Machine Shop | Shop TA level 1 | 32 | 140.58 | 0.00 | 140.58 | 0 | 0.00 | 0.00 | 0.00 | ? |
| | Machine Shop | Shop TA level 1 | 40 | 138.62 | 0.00 | 138.62 | 0 | 0.00 | 0.00 | 0.00 | ? |
| | shop floor | Shop TA level 1 | 22 | 25.00 | 0.00 | 25.00 | 0 | 0.00 | 0.00 | 0.00 | ? |
| | Machine Shop | Shop TA level 1 | 130 | 471.60 | 0.00 | 471.60 | 0 | 0.00 | 0.00 | 0.00 | ? |
| | Machine Shop | Shop TA level 1 | 50 | 92.07 | 0.00 | 92.07 | 0 | 0.00 | 0.00 | 0.00 | |
| | shop floor | Shop TA level 1 | 1 | 8.25 | 0.00 | 8.25 | 0 | 0.00 | 0.00 | 0.00 | |
| | Machine Shop | Shop TA level 1 | 23 | 102.70 | 0.00 | 102.70 | 0 | 0.00 | 0.00 | 0.00 | ? |
| | shop floor | Shop TA level 1 | 48 | 291.00 | 0.00 | 291.00 | 0 | 0.00 | 0.00 | 0.00 | ? |
| | Machine Shop | Shop TA level 1 | 13 | 48.38 | 0.00 | 48.38 | 0 | 0.00 | 0.00 | 0.00 | |
| | Machine Shop | Shop TA level 1 | 41 | 78.95 | 0.00 | 78.95 | 0 | 0.00 | 0.00 | 0.00 | ? |
| | Machine Shop | Shop TA level 1 | 6 | 18.67 | 0.00 | 18.67 | 0 | 0.00 | 0.00 | 0.00 | |
| | shop floor | Shop TA level 1 | 14 | 49.03 | 0.00 | 49.03 | 0 | 0.00 | 0.00 | 0.00 | |
| | shop floor | Shop TA level 1 | 102 | 342.35 | 0.00 | 342.35 | 0 | 0.00 | 0.00 | 0.00 | ? |
| | Machine Shop | Shop TA level 1 | 1 | 4.00 | 0.00 | 4.00 | 0 | 0.00 | 0.00 | 0.00 | |
| | Machine Shop | Shop TA level 1 | 78 | 185.55 | 0.00 | 185.55 | 0 | 0.00 | 0.00 | 0.00 | ? |
| | Machine Shop | Shop TA level 1 | 62 | 120.35 | 0.00 | 120.35 | 0 | 0.00 | 0.00 | 0.00 | ? |
| | Machine Shop | Shop TA level 1 | 50 | 369.63 | 0.00 | 369.63 | 0 | 0.00 | 0.00 | 0.00 | ? |
| | shop floor | Shop TA level 1 | 56 | 384.20 | 0.00 | 384.20 | 0 | 0.00 | 0.00 | 0.00 | |
| | Machine Shop | Shop TA level 1 | 32 | 210.28 | 0.00 | 210.28 | 0 | 0.00 | 0.00 | 0.00 | ? |
| | Machine Shop | Shop TA level 1 | 33 | 103.65 | 0.00 | 103.65 | 0 | 0.00 | 0.00 | 0.00 | ? |
| | Machine Shop | Shop TA level 1 | 28 | 115.82 | 0.00 | 115.82 | 0 | 0.00 | 0.00 | 0.00 | ? |
| | Machine Shop | Shop TA level 1 | 29 | 96.92 | 0.00 | 96.92 | 0 | 0.00 | 0.00 | 0.00 | ? |
| | Machine Shop | Shop TA level 1 | 39 | 131.45 | 0.00 | 131.45 | 0 | 0.00 | 0.00 | 0.00 | ? |
| | shop floor | Shop TA level 1 | 72 | 169.08 | 0.00 | 169.08 | 0 | 0.00 | 0.00 | 0.00 | ? |
| | Machine Shop | Shop TA level 1 | 67 | 212.58 | 0.00 | 212.58 | 0 | 0.00 | 0.00 | 0.00 | ? |
| | Machine Shop | Shop TA level 1 | 10 | 17.02 | 0.00 | 17.02 | 0 | 0.00 | 0.00 | 0.00 | ? |
| | shop floor | Shop TA level 1 | 90 | 353.80 | 0.00 | 353.80 | 0 | 0.00 | 0.00 | 0.00 | ? |
| | Machine Shop | Shop TA level 1 | 31 | 222.18 | 0.00 | 222.18 | 0 | 0.00 | 0.00 | 0.00 | ? |
| | Machine Shop | Shop TA level 1 | 9 | 21.30 | 0.00 | 21.30 | 0 | 0.00 | 0.00 | 0.00 | |
| | | **Total** | **2009** | **8,654.65** | **0.00** | **8,654.65** | **0** | **0.00** | **0.00** | **0.00** | |