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The Impact of Hands-on Geometric Dimensioning and Tolerancing Intervention Activities on Students In Engineering Design

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ABSTRACT

In many mechanical engineering undergraduate curriculums, there are topics that are vital to the students' future careers in the manufacturing and design workforce that are not taught in-depth. As one of those topics, Geometric Dimensioning and Tolerancing, or GD&T, is vital to companies who develop and manufacture products because it allows one to communicate with other team members in order to produce and inspect manufactured parts. GD&T is filled with intricate concepts that are hard to grasp without repetition and practice. An active learning intervention was developed and deployed in a mechanical engineering undergraduate class at the Georgia Institute of Technology. The active learning interventions were developed to assist students in learning basic manual inspection methods and communicating through a part drawing. The goal was for the students to obtain a foundational, hands-on understanding of GD&T and implement their learnings onto a part drawing and inspection plan. The results of this intervention were based on a Knowledge Assessment, self-reported Self-Efficacy Survey, and an Exit Survey. These assessments revealed that the GD&T intervention had a significant impact on the students' knowledgebase of the topic and their ability to perform identification and inspection tasks used in the workforce. This paper discusses the intervention structure and its potential applications for engineering education in the workforce.

Key words: Experiential Learning, Student Assessment, Engineering Curriculum

INTRODUCTION

Geometric Dimensioning and Tolerancing (GD&T) is a subject in mechanical engineering that is widely used in design for manufacturing, and there is a high demand for competency in GD&T for graduates entering the workforce. This topic is often taught in a highly theoretical manner, with symbols, abbreviations, and references. Students in the first two years of introductory engineering classes are exposed to this topic, and it is a major component of activities that will be taught in the other classes as the students progress through their education, and beyond in their future engineering careers.

GD&T is a system primarily used for part design and manufacturing in industrial settings. GD&T helps define and communicate design intent for specific part designs between engineers and manufacturers. These parts are created individually to be combined as a whole. Starting with CAD, the engineers design the parts, add the tolerances and characteristics of the design that are important, then send the part drawings with these specifications to be manufactured. The manufacturing team uses the part drawing to develop, then inspect the manufactured part to determine if it is acceptable from the specifications communicated through GD&T. This process is important for those engineers who want to pursue product and engineering design everywhere.

This paper presents the development process and validation of an intervention for GD&T that is designed to help the students obtain a deeper understanding outside of a traditional lecture. The active learning GD&T intervention ties together major concepts with hands-on practice for topics that are prevalent in GD&T. Although in industry, coordinate measuring machines (CMMs) are most typically used for inspecting machined parts for the outlined specifications, the students were asked to perform manual methods of inspection during the intervention. By exercising their knowledge of GD&T using manual inspection methods, students were exposed to the necessary background to understand what measurements are needed for part feature inspections and how to translate them to the CMM. The active learning intervention allowed the students to grasp the reasoning behind automated CMM inspection methods. The intervention provided students with a foundational understanding of GD&T, which allowed them to understand the concepts to create part drawings that communicate the correct tolerances needed for manufacturing and assembly.

BACKGROUND

Geometric Dimensioning and Tolerancing is used in design and manufacturing as a method of communicating how a part is used and what tolerances a part should be manufactured to meet.

Part specifications are important to engineering designers because products need to be designed for certain functions and design intent. GD&T is a language with which designers and machinists communicate to reach the goal of delivering an acceptable part. In undergraduate curricula, many students are not taught the breadth of information associated with GD&T. There are limited studies primarily focused on the subject because of its specificity, typically being taught as a supplement to a manufacturing or design course (Branoff 2018a; Branoff 2018b; Yip-Hoi and Gill 2017; Devine 2012; Sriraman and Leon 1999). This paper combines active learning and GD&T into an intervention where assessment and survey metrics are analyzed to understand the impact of a miniature GD&T intervention on the students' knowledgebase and self-efficacy.

Active Learning in Engineering

Active learning is presented in this paper through problem-based learning and hands-on learning. Problem-based learning (PBL) is an instructional method that introduces specific problems relevant to the course material at the beginning of the lesson to be used as context for the concept(s) to follow (Prince 2004), or developing problem solving skills with proper support from the instructors (Hood Cattaneo 2017). Problem-based learning is an active learning methodology that has become immensely popular as an educational intervention since its establishment at McMaster University in Canada by Don Woods (Neufeld and Barrows 1974). The main benefit of problem-based learning is the ability for students to have an application or workplace-based experience in the classroom instead of memorizing and repeating knowledge.

In addition, the adaptation of problem-based learning has translated to the engineering field (Nizaruddin, Muhtarom, and Zuhri 2019; Othman et al. 2017; Arsani et al. 2020). This method has been seen as an effective approach to linking the material being taught in engineering to real-world problems that students will encounter after graduation (Nizaruddin, Muhtarom, and Zuhri 2019). Researchers determined that problem-based learning sets students up for immediate academic success in engineering classrooms and the pre-requisite courses for mechanical engineering students.

Hands-on learning is an instructional method involving one or more items for students to observe and interact with as they learn about the intended topic. Students are given objects to look at and manipulate, thereby leveraging several senses to focus cognitive attention on sensory inputs to increase learning(Bonwell and Eison 1991; Prince 2004). Further, the act of manipulating physical objects will facilitate an instructor's ability to prompt students to engage effectively in active learning. In some cases, students will create the 3D objects themselves, which will further increase the cognitive engagement of students. Learning is likely to improve when students are given the opportunity to engage with the materials through a variety of channels of input (e.g. sight, touch, hearing), provided the cognitive load of the multiple inputs is appropriately managed (Moore, Burton,

and Myers 2004). Even though hands-on learning has been pushed in the past as a way to promote better learning outcomes in students, Schwichow et al. suggests that it does not matter if the activity is physical or virtual; cognitive processes are occurring in some form (Schwichow et al. 2016).

Active Learning in GD&T

Although active learning has spanned a multitude of topics in classroom and professional settings, there has not been much progress towards understanding the impact of this teaching and learning style in the manufacturing, more specifically GD&T, realm. Because it is heavily tied to manufacturing, the concepts are often incorporated into manufacturing courses in colleges. In the past years, GD&T non-traditional lecture activities have been implemented in the classroom. Dean Watts from Hewlett Packard discusses the relevance of the "GD&T Knowledge Gap", which causes companies to pay for GD&T training to prevent misinterpreted drawings, incorrectly manufactured parts, and high costs due to rework caused by an inadequate understanding of GD&T (Watts 2007). Watts emphasizes that hands-on experience is key to addressing the "GD&T Knowledge Gap" by providing students with real measurement equipment and practical experience. However, hands-on training can be cost-prohibitive for some universities (Denizhan and Chew 2020) thus leaving companies to cover the training cost and pay anywhere from $1200–$2000 dollars per class for basic GD&T training (Waldorf and Georgeou 2016). Due to the cost associated with GD&T training per employee, GD&T knowledge is becoming a sought-after skill on a potential candidate's resume (Waldorf and Georgeou 2016). Thus, this research proposes a novel, cost-effective way to teach hands-on GD&T to university students to help reduce the "GD&T Knowledge Gap" and better prepare students for the workforce.

GD&T basics, such as understanding tolerances and symbol meanings, were introduced through simple hands-on experimental acrylic models to an introductory first-year design class at Georgia Tech to help students visualize the concepts when learning a basic overview (Paige and Fu 2017). Yip-Hoi, at Western Washington University, took a design for manufacturing approach in teaching students GD&T by allowing them to design parts using manufacturing processes based on self-annotated GD&T drawings (Yip-Hoi and Gill 2017). GD&T instruction was used in a design graphics course at Southwest Texas State University, where students were explained GD&T in three parts to help them understand why it is used and how the inspection is performed on a Coordinate Measuring Machine (CMM) (Sriraman and Leon 1999). At University of Texas, Dallas, concepts, such as tolerance zones, datums, and material conditions (most/least material conditions - MMC/LMC), were illustrated through 3D computer models and 3D printed parts. These interventions resulted in benefits to students' learning from the 3D technology (Rios 2018).

Although the concepts have been taught to students as activities embedded in other curricula, Illinois State University offered TEC333 - Geometric Dimensioning & Tolerancing in Fall 2015 as a

stand-alone course (Branoff 2018a; Branoff 2018b). Branoff studied the ways in which the course's structure impacted the students' learning though a pre-test, weekly quizzes, exams, and lab activities during the Fall semesters of 2016 and 2017. Branoff found that there was a benefit to evaluating all of the data collected since it gave a comprehensive understanding of concepts the students failed to grasp well throughout the course and an idea of what to focus on in future semesters of TEC333 courses (Branoff 2018b). The data demonstrated the students' improvement on some GD&T topics, but there remained some topics to be emphasized when teaching in subsequent semesters.

Self-Efficacy and Active Learning

Self-efficacy is the belief in a person's self-perceived competence to complete certain tasks or actions. Although efficacy is often confused with confidence, Hutchison et al. explains the difference is that self-efficacy is based on a "specific level of attainment and the strength of one's belief the at the level of attainment can be achieved (Hutchison et al. 2006). Bandura's social-cognitive theory explains that self-efficacy is a major predictor in many facets of a student's academic life (Bandura 1997, 1986), such as academic achievement (van Dinther, Dochy, and Segers 2011), personal choice of fulfilling activities (Hutchison et al. 2006), and persistence and resilience (Pajares 1996).

Active learning has been a teaching model that has helped cultivate an increased self-efficacy of students in courses as well as academic performance. Active learning techniques means a greater range of learning experiences for students which can positively impact self-efficacy (Duchatelet and Donche 2019). On a broad level, researchers, such as Hayward, used surveys to understand the overall picture of active teaching and academic self-efficacy in STEM courses (Hayward 2020). His findings revealed that increased academic self-efficacy is associated with better course grades, students' course persistency, and expectancy for success. Also, self-efficacy has been studied to understand the impact of a problem-based learning design capstone course class on the student's confidence in their ability to succeed in the future as a software professional (Dunlap 2005). This effort resulted in the increased general perceived self-efficacy of the students' professional abilities from the pre-PBL environment to post-PBL environment.

On a smaller scale, active learning and self-efficacy has been examined in mechanical engineering capstone classes to investigate the impact of particular self-efficacy self-concepts to complete design tasks (Tsenn, Lewis, and Layton 2019). Tsenn et al. explored how senior design projects impacted the students' confidence, motivation, success, and anxiety to conduct nine future design tasks and revealed that design self-efficacy is associated with the amount of effort the student puts forth (Tsenn, Lewis, and Layton 2019). This work explores self-efficacy from a similar task-based perspective of self-efficacy, but the tasks are ones the student is asked to perform in the active learning activities.

Value and Expectancy on Learning and Performance

Motivation for student learning and engagement has been examined by Ambrose as it pertains to the impact of value and expectancy on learning and performance. Ambrose explains the more students value a goal and expect success in attaining the goal, the greater their motivation will be to pursue it (Ambrose 2010). Value, particularly in terms of goals, is a key feature of motivation influence. When one accomplishes a goal or task, they gain satisfaction and therefore that experience they went through is deemed valuable. Efficacy expectancies, such as the belief that one is capable of doing work to make a grade rather than simply doing the work to earn a grade are essential for motivation and engagement (Bandura 1997).

Ambrose proposed actions for instructors to help increase students' motivation for student learning and engagement. One action is recognizing that instructors and teaching quality are central to the engagement of students; for example, the instructor is providing deep learning experiences (Kuh et al. 2006), a supportive learning environment visible to the students (Bryson and Hand 2007), or an approachable and supportive instructor (Mearns, Meyer, and Bharadwaj 2007; Reason, Terenzini, and Domingo 2006). Another proposed action is to create learning that is active, collaborative, and fosters learning relationships. Active learning in groups, in addition to student's outside-of-class peer interactions and social skills, is important in engaging students (Zepke and Leach 2010). Moran and Gonyea revealed that peer interaction supported students' engagement and outcomes (Moran and Gonyea 2003). These interactions with peers can lead to improved social skills and higher scores on course assessments. In this work, the combination of value and expectancy has been introduced through a supportive active learning environment where the researchers fostered that instructor-student relationship and allowed the students to interact with peers in groups to help support student engagement to yield more favorable outcomes.

Another strategy that was proposed to address the combination of value and expectancy was to give the students the opportunity to reflect on their assignments (Ambrose 2010). Self-assessment has been shown to improve self-efficacy in the educational space. Panadero et al. believes "...having students assess their progress makes it clear to them that they have become more competent, which in turn strengthens their self-efficacy" (Panadero, Jonsson, and Botella 2017). Allowing the students to give feedback and reflect on their experience and their progress gives the students a space to acknowledge their strengths and weaknesses. Students who believe they are capable of the specified tasks will be more willing to participate in class activities than those who have a low sense of self-efficacy (Schunk 1996). This acknowledgement helps the students understand their shortcomings and where they could improve in the long-run if the tasks align with their goals – in this case, the goal is academic achievement.

In this work, the students were asked to reflect via surveys. These surveys asked how valuable the students believed certain portions of the project were and their opinion on what they expected from the modules in the future.

In this paper, the effect of careful development and deployment of an active learning intervention focused on GD&T into an undergraduate level class is explored. This intervention connects hands-on activities with needed manufacturing engineering practice to promote self-efficacy and knowledge retention. The intervention incorporates a traditional lecture in conjunction with active learning activities to disseminate information to the students while encouraging them to explore on their own. The intervention included machined parts developed with purposeful characteristics, manual inspection tools to determine if the part meets the specifications, and a step-by-step guided inspection activity. Formative and self-assessments were used to gather participant feedback and performance information to evaluate the educational impact of the developed interventions. The data was analyzed and translated into recommendations for information and concepts to be implemented in future designs of the intervention.

ACTIVITY DEVELOPMENT AND COMPONENTS

There are many different factors that prompt those in industry and other manufacturing spaces to invest into in-depth GD&T training, including improved communication, reduction in manufacturing costs and simplified inspections (Bramble 2013). In manufacturing, inspection of a part's elements relies heavily on the characteristics identified in the part's drawing. An active learning intervention style lecture was paired with five manual inspections on a machined part to enhance the students' understanding of GD&T concepts within the given time constraints of their course. The objectives and expectations of the students in this intervention were:

By the end of this GD&T Intervention, students should be able to:

- Produce a part drawing that communicates GD&T information to a machinist and inspector
- Demonstrate manual inspection methods for various GD&T characteristics
- Identify and interpret GD&T symbols
- Explain the function of and how to use a Coordinate Measuring Machine (CMM)

The GD&T intervention consisted of three parts: Lecture, Activity 1: Part Drawing, and Activity 2: Inspection Activity. These sections were accompanied by Pre-Assessments and Post-Assessments that helped the research team to understand if the intervention made an immediate impact on the capabilities of the students. In Activity 1, the students were asked to fill in a part drawing based on the information given about the manufacturability and function of the part. In Activity 2, the students performed a hands-on manual inspection activity based on given part drawing specifications and methods outlined. These assessments are described in detail later in the paper.

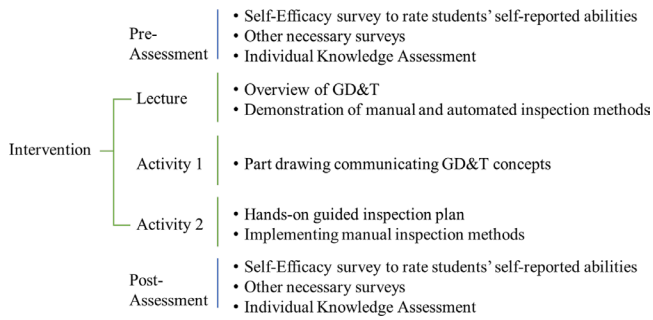


Figure 1. Breakdown of GD&T Intervention components.

Lecture

The lecture about GD&T basics was a crucial part of this study and was delivered by two lecturers. The lecture was used to provide participants with the information needed to perform the part drawing and hands-on activity portions of the intervention. The lecture framed the GD&T information in the context of the history of manufacturing in order to explain why GD&T standards are used in industry. By explaining the evolution of manufacturing from manually created single parts, to the beginning of mass production, to the need for accurate mass-produced parts, the need for GD&T standards became clear. The lecture included the purpose and selection process of datums so that students would be able complete the part drawing when given the physical part. For the same reason, symbols and feature control frames were covered next before the in-depth explanation of the different types of tolerances. These tolerances included: datums, flatness, perpendicularity, parallelism, hole size, position of a hole, and profile of a surface. The types of tolerances selected for in-depth instruction were the ones utilized in the hands-on activity, as outlined in the following section. The detailed instruction contained a description of the tolerance with visual aids, an example of its usage in an engineering drawing, and methods used to measure the tolerance. Measurement methodology included high-end examples, such as a coordinate measuring machine (CMM), less advanced mid-range methods, and the low-cost methods utilized in the hands-on portion of the activity.

Machined Part

In Activity 1 and Activity 2, students used two mating machined parts (Part A and Part B) as visuals and tools for collaboration and inspection, as shown in Figure 2. The machined part was designed to mimic the form and function of a part that would commonly be produced in a machine shop. The parts have interlocking features: Part A has two holes in the center, and

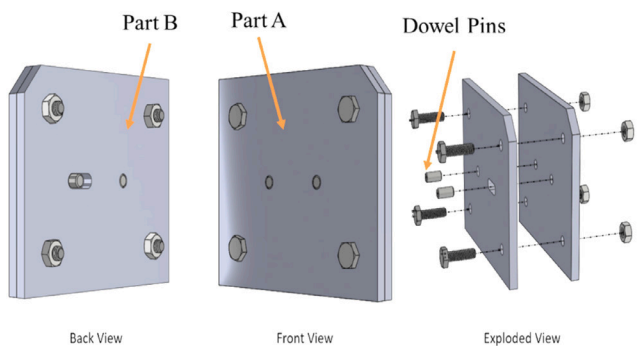


Figure 2. Back, front, and exploded view of Parts A and B.

Part B has a slot and a hole that line up with Part A's holes to allow dowel pins to be inserted. Hole/slot alignment is a preferred and common way to align two parts without resulting in over-constraining and higher machining costs, while still maintaining precision location. Understanding how to use GD&T to effectively communicate datum features and part tolerances for hole/slot alignment is a useful skill for mechanical designers. Part A and B, shown in Figure 2, have common features - the part is a flat rectangular block with four bolt holes in each corner, and one corner cut at a 45-degree angle for orientation. The 45-degree angle notch is to help students to reference part orientation in regard to the engineering drawing. Four holes were added around the hole/slot alignment feature to give the students additional features to learn from. Understanding how to use GD&T to communicate how to manufacture this part to a mechanic is a useful skill for developing engineers to ensure part functionality. Having additional bolt holes around a hole/slot alignment can be common for parts that require redundancy in the event that the dowel pins fail.

In this intervention, Part B is the machined part of focus. Part B was the only machined part used for inspection due to time constraints, social distancing restrictions in the classroom, and because the inspection method for Part B incorporated a functional gauge for the hole/slot combination, unlike Part A, thus introducing the students to a larger variety of inspection techniques.

Activity 1: Part Drawing

Activity 1 was developed with the intention that the participants would apply the characteristics and concepts outlined in the lecture to a physical part drawing of the machined part, as shown in Figure 3. The students were given a blank part drawing to fill in part specifications. The specifications included in the part drawing were intended to be guides for understanding how specifications translate from form and function to certain necessary inspection methods. The activity contained

Figure 3. Machined Part B with hole and slot and four corner holes.

an explanation of how the parts were intended to be used in order to help students understand how the certain part features interfaced with others.

Participants were given a packet of paper materials for the intervention. The packet supplied a list of GD&T characteristics and terms, such as datums and tolerances, that were expected to be used in the filled-in drawing. The students were tasked with filling the blanks in based on the information given in the packet. This task was designed to be completed individually and to the best of their ability. After the students completed the activity, they were given the correct part drawing with the necessary specifications, as shown in Figure 4, to inspect and measure the machined part for Activity 2: Inspection Activity.

Activity 2: Inspection Activity

The inspection activity was developed for the participants to be able to perform a reasonable manual inspection of the aluminum part (Figure 3 above) given the part drawing. A manual inspection is important because one will be able to gauge if a part meets the specifications (or "is in-spec"), but also will be able to verify the CMM if they suspect something may be wrong or mis-calibrated. Although inspections in the present day are typically performed using the CMM, these manual inspection methods were incorporated into the activity to give the students an understanding of how the different characteristics are tested and how certain features of a part are measured. It is important for the students to be able to interpret GD&T in part drawings regardless of inspection method.

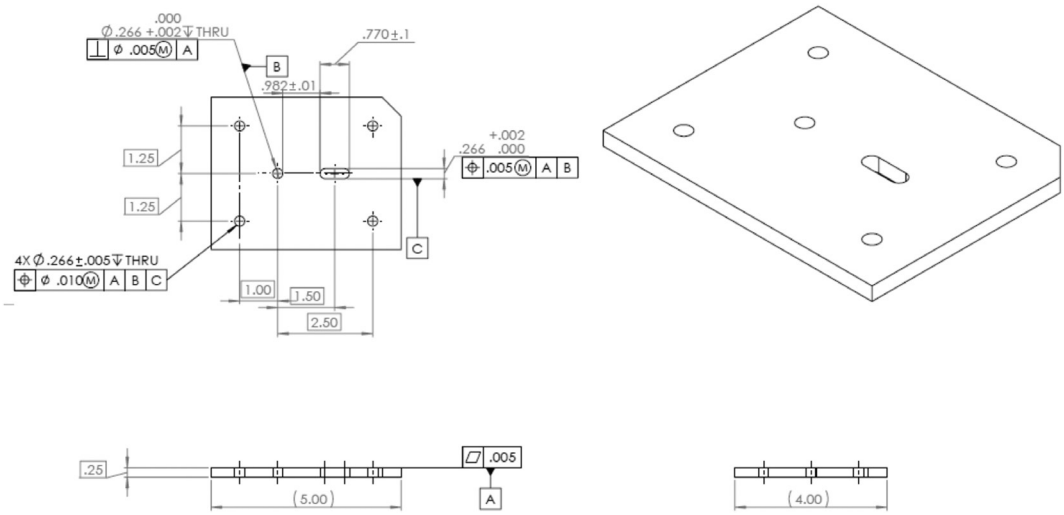


Figure 4. Part drawing of Machined Part B.

The five inspection methods and materials used for the inspection activity are outlined in Table 1. These inspection methods were selected and developed due to the low cost (the price of one kit was slightly over $300), as well as the accessibility of the methods. Many of the methods could be performed without specialized equipment and would therefore be more applicable to future situations in which the participants need to verify if a part is manufactured correctly but may not have high-cost specialized measurement equipment available. The combination of these materials for inspection will be comparable to a CMM inspection method of the same features.

Table 1. Description of inspection activities.

Flatness	Participants used the granite slab and 1-2-3 gauge blocks to level the feature, then swept the surface with the horizontal dial indicator to determine if the part was flat.
Slot size	Participants used a caliper to measure the major and minor diameters of the stadium-shaped slot to determine if the dimensions were in spec.
Hole size	Participants used the "no-go" gauge pins to check that the hole diameter was within the upper tolerance. They used a "go" gauge pin to check the lower tolerance.
Hole position	Participants measured the distance between holes by placing "go" gauge pins in two holes. The calipers were then used to measure the distance between the pins, while using the machinist's square to ensure that the caliper was held parallel to the part edges. Participants took measurements in both the x- and y-direction before performing an MMC calculation to ensure that the hole position was within spec.
Position of hole and slot	Participants used the custom steel functional gauge to determine if the position of the hole and slot were within spec. If the gauge was able to be fully inserted into the cutouts, then the part was in spec.

Each participant was given a kit of inspection materials to obtain measurements of their aluminum part and determine whether each measurement was in- or out-of-spec according to the correct part drawing granted after the student completed Activity 1 of the activity. The kit consisted of go/no-go gauges, a granite block, a machinist's square, a horizontal dial indicator, a functional gauge, calipers, and a 1-2-3 gauge block. Each inspection method had written instructions for use of materials to obtain the necessary measurements. Along with the instructions, there is a table where the measurements are recorded. In the beginning of the Part 2 section of the packet, there was a master table with space to put necessary information needed to determine if the part's features were in spec. For brevity, two methods will be discussed in this paper: position of the hole and slot and the flatness inspection method.

For the position of hole and slot method, the students were given a custom, machined steel functional gauge shown in Figure 5. This functional gauge was essential for determining the accuracy of the hole position in relation to the slot position. If the gauge was able to be fully inserted into the hole and slot of the aluminum part, then the part was defined as in-spec, and the students were asked to note this in their activity packet. Figure 6 illustrates this inspection method.

For the flatness inspection method, the students used a granite slab, two 1-2-3 gauge blocks, and a horizontal dial indicator, all shown in Figure 7. The granite slab had precise manufacturing specifications; therefore, making it a good surface to use for a leveled plane in comparison to the existing wooden tables. The 1-2-3 gauge blocks are used as a second level feature for the machined part rests on top of the gauges, which rests on top of the granite block. These second level features are needed to elevate the machined part to use the horizontal dial indicator. The horizonal dial indicator was swept to four points on the surface of the machined part to determine the part's flatness. The comparison of the change in reading of the four points from the calibration point to the flatness specifications on the part drawings determined if the part was in spec or not. This inspection method is shown in Figure 8.

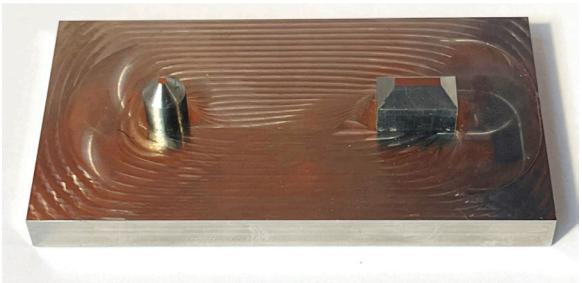


Figure 5. Machined functional gauge used for position of hole and slot inspection method.

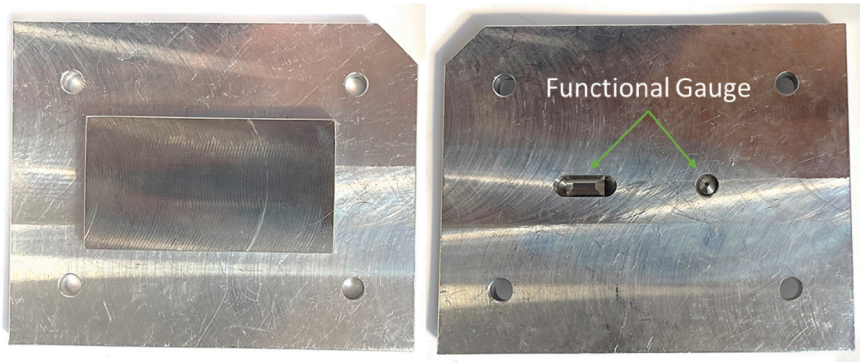


Figure 6. Position of hole and slot inspection method using functional gauge from the front view (left) and back view (right).

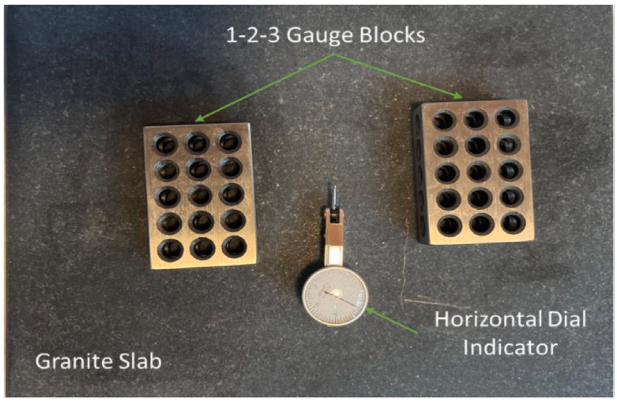


Figure 7. Materials used for flatness inspection method.

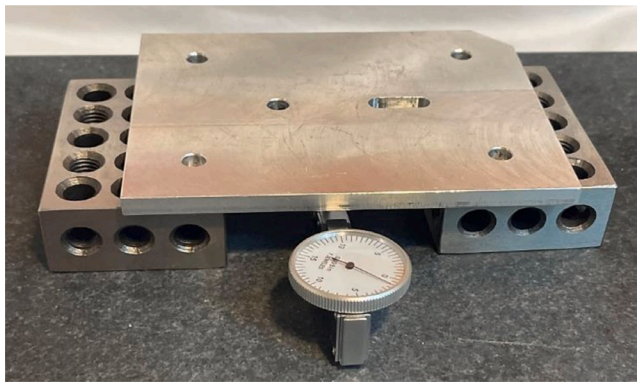


Figure 8. Flatness inspection of Machined Part B.

Assessments and Surveys

Two types of assessments were used to help the researchers understand the impact of the intervention on the students: a Knowledge Assessment and a Self-Efficacy Assessment. Two surveys were used to understand if the students believed the activities contributed to their comprehension of the GD&T topic: Exit Survey and Perceived Value survey.

Knowledge Assessment

The students were given the same Knowledge Assessment before and after the intervention. The Knowledge Assessment questions were tailored to the skills or knowledge students were expected to gain during the lecture and activities given. The assessment consisted of eight questions that asked the students to identify geometric characteristics and symbols, fill in the necessary part drawing characteristics, accept or reject a part, and other topic-specific knowledge students would gain from the activities. The questions were created based on the lecture teachings and topics that were covered. For the part drawing (Figure 9), the students were given instructions on how to fill in the necessary parts of the feature control frame. This was added to help the researchers understand if students knew the best method to assign datums and if they recognized the placement and dimensioning associated with the GD&T guidelines.

4. Fill in the necessary information into the feature control frame (FCF) for the following part
   a. Establish the right-hand face in the left-side view as datum feature A.
   b. Label datum features B and C.
   c. Label the primary and secondary datums missing in the FCF.
   d. Label the GD&T characteristics for profile of surface, position, flatness, and perpendicularity.

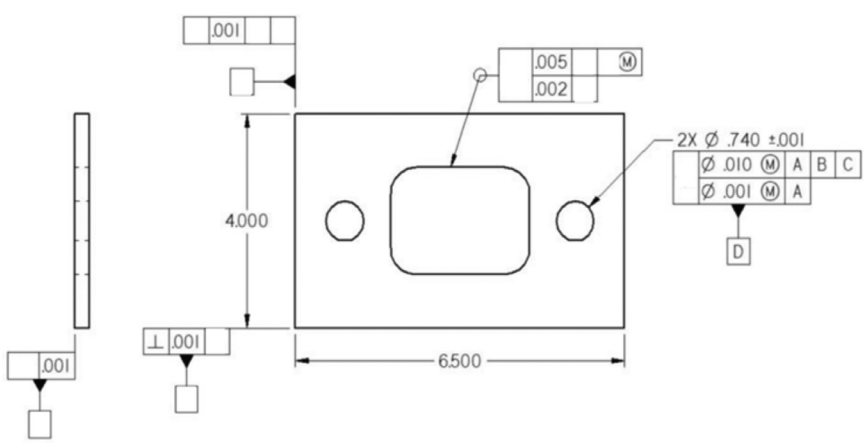


Figure 9. Question 4 (Part Drawing) from the Knowledge Assessment.

The students were scored out of 29.5 points. Each blank of the part drawing was worth 0.5 points. The free response questions had 0.5-1 point flexibility if the student answered the question, but did not have a clear, concise answer. The GD&T characteristics and symbols in the other questions were worth 1 point each. The Knowledge Assessment and the corresponding points system were created to distribute the weight of the information asked of the students. This helped the researchers understand what concepts the students may not have grasped, as well as avoid penalization of the overall student score if one concept was not grasped over others.

Self-Efficacy Assessment

The students were given a self-reported Self-Efficacy Assessment before and after the Knowledge Assessment to help the researchers understand their confidence in their ability to complete certain tasks. These tasks were specific to the expectations of topics or methods students should have learned in the activities. Self-efficacy was used as an alternative method of gauging the students' progression from before to after the activities. The students rated their confidence of their ability to complete the following tasks on a scale from 1 (Cannot do at all) to 5 (Highly certain can do). The self-efficacy scale was adopted from Bandura's Guide for Constructing Self-Efficacy Scales (Bandura and Bandura 2006) and the Likert-scale adaptation made by Pajares et al (Pajares 1996).

1. Identify Geometric Dimensioning & Tolerancing (GD&T) symbols
2. Choose correct reference datum based on part description
3. Calculate Least Material Condition (LMC) of specific hole
4. Calculate Maximum Material Condition (MMC) of specific hole
5. Create a Feature Control Frame (FCF)
6. Interpret a Feature Control Frame (FCF)
7. Measure the flatness of a feature using horizontal dial indicator
8. Measure the perpendicularity of a hole using gauge pin and dial indicator
9. Measure hole position using calipers and machinist square
10. Measure a hole size using go/no-go gauge pins
11. Measure a hole position using a gauge pin calipers and a machinist square
12. Verify the position of features relative to each other using functional gauge
13. Accept or reject features based on measurements conducted
14. Use a manufacturing method to decide the tolerance of a hole
15. Understand how to set up a part in a CMM (Coordinate Measuring Machine)

Exit Survey

The students were given an exit survey at the end of the intervention. The survey asked the students six Likert scale questions and three open response questions. Five of the questions asked

the students to agree or disagree (1 – Strongly disagree and 5 – Strongly agree) to if the activities contributed to the students' knowledge, and the sixth question asked the students to rate the usefulness (1 – Not useful at all, 2 – Slightly useful, 3 – Moderately useful, 4 – Very Useful, 5 – Extremely useful) of the overall intervention. The three open response questions asked what the students believed were the best parts of the intervention and what they believe the researchers could do to make sure the intervention in better in the future.

Perceived Value

The perceived value survey asked students about components that were essential to the intervention, and students indicated whether they saw value in those components. The survey used a 5-point Likert scale (1 – Completely disagree, 2 – Somewhat Disagree, 3 – Neither agree nor disagree, 4 – Somewhat Agree, 5 – Completely Agree).

ACTIVITY IMPLEMENTATION

The activities were implemented in two 3-hour lab sections of the ME2110 course. The activity took roughly two hours of the lab session. Participation was strictly volunteer based, and the students were compensated with extra credit if they participated. The intervention was broken down into five parts (Figure 10): Pre-Knowledge Assessment (which incorporated the pre Self-Efficacy survey), Informational Lecture, Activity 1: Part Drawing, Activity 2: Measuring Activity, and Post-Knowledge Assessment (which incorporated the post Self-Efficacy survey, Exit survey, and Perceived Value survey). The Knowledge Assessments were given at the beginning and end of the sessions. The students were given 10 minutes to complete each of the Knowledge Assessments and accompanying surveys. They were then given a 45-minute lecture of an overview of the importance of GD&T, main concepts, and how measurements are done manually and on the CMM. After, the lecture, the students were given 20 minutes to complete Activity 1 and 40 minutes to complete Activity 2 of the intervention.

Activity 1: Part Drawing

The first part of the intervention was completed individually. During this time, the students were asked to spend 20 minutes understanding the functionality of the part and filling in the respective

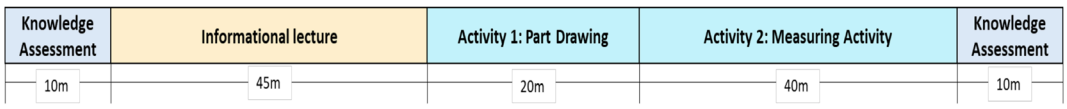


Figure 10. Schedule of Activities.

GD&T symbols for the part drawings. After the students completed this task, their part drawing was photographed to make sure they did not go back and change anything, then they were given a correct part drawing to use for measuring activities in Activity 2.

Activity 2: Inspection Activity

For Activity 2, the students were divided into groups of 2-3 students. Each student had their own physical machined part to measure, but shared inspection materials and techniques. Group learning was incorporated to encourage students to think about and share ideas that could help them successfully inspect the machined parts. The material that was mainly shared by the group was the granite block. Each student had their own gauges, calipers, and other necessary materials. Half of the machined parts were created in adherence with a master part drawing, while the other half of the parts were created in violation of the drawing in order to test whether the groups of participants were able to differentiate between in-spec and out-of-spec parts.

Observations

The first session happened in the morning while the second session happened in the afternoon, therefore the implementation team was better equipped for running the evening session due to the lessons learned in the first session. In both sessions, the implementation team realized that the time allotted was a crucial factor in the experience of the students in the study. The timing of the activities was not sufficient for the students to work on everything given. Since this was the first time many students were exposed to an in-depth GD&T lecture and activity, the students appeared confused and required more explanation than the provided lecture. This took up much of the time, and the students tried their best to complete as much of the activities as possible.

For Activity 1, the students did take the time to fill out the part drawing, but because it was not mandatory to move forward, they did not feel the need to struggle on the activity. Although, the students were given a list of features to incorporate in the drawings, many students chose not to fill in the majority of the part drawing and instead move on to the second part. For Activity 2, the students were not able to complete all parts in the time allotted. They had many questions about how to set up the inspection tools for the various inspection parts. The main inspection method requiring instructor help was the flatness inspection. This involved a horizontal dial indicator and the students setting the inspection tools up in a specific manner to inspect the part. This prompted the instruction team to help walk the students through the instrumentation set up and to display the relevant slides from the lecture on the screen so that students were able to reference them. Instead of reading the instructions in the packet, many students asked the instructors to explain the procedure to them or attempted to figure it out on their own by experimenting with the provided

materials. Many of the students were not able to get to the inspection of hole size activity due to time constraints.

RESULTS

The results of the GD&T intervention activity are extensive. The results presented in this paper will explore the demographic composition of the classes, the surveys the students completed, the activities the students participated in, and the correlations between these different data channels.

Demographics

In this study, students were recruited from the ME2110 sophomore level creative design course at Georgia Institute of Technology. There were 29 participants in total, but one chose not to disclose demographic data. The first session had 11 participants, and the second session had 18 participants. Overall, there were 22 men and 6 women participants. The primary age range identified by the participants was 20-22 years old. The participants' year in their undergraduate studies had an average of 2.75 years and ranged from 2-5 years. The students were all mechanical engineering majors besides one student from the college of business who is pursuing a minor in mechanical engineering. There were 14 students with one or more minors spanning at least six different colleges at Georgia Tech.

For GD&T experience, 16 participants had prior experience with GD&T. Most of the prior GD&T experience was from class, most notably the ME1770 class at Georgia Tech. Figure 13 shows the breakdown of the types of GD&T experience the participants had previously. Every participant had hardware tool experience, ranging from the band saw and drill to a CNC machine. Every participant

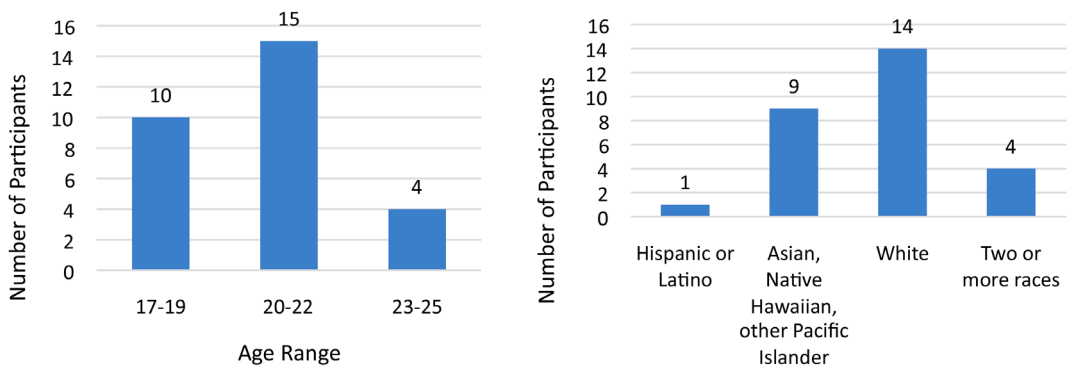


Figure 11. Age Range of Participants (left) and the Race and Ethnicity distribution of participants (right).

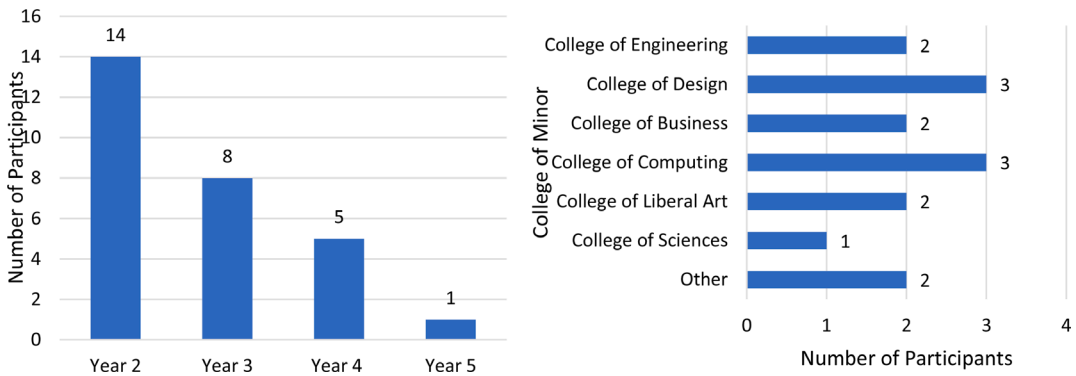


Figure 12. Year of undergrad distribution of participants (left) and minor college enrollment distribution of participants (right).

had experience with a CAD or design software, ranging from SolidWorks and Inventor to Adobe Suite.

The participants were asked their how many years of fabrication-related and design-related experience they had, excluding the ME2110 class deliverables. Most participants did not have either fabrication or design-related experiences outside of class. Figure 14 shows the years of experience distribution for both design and fabrication. Only one participant had more than two years of both

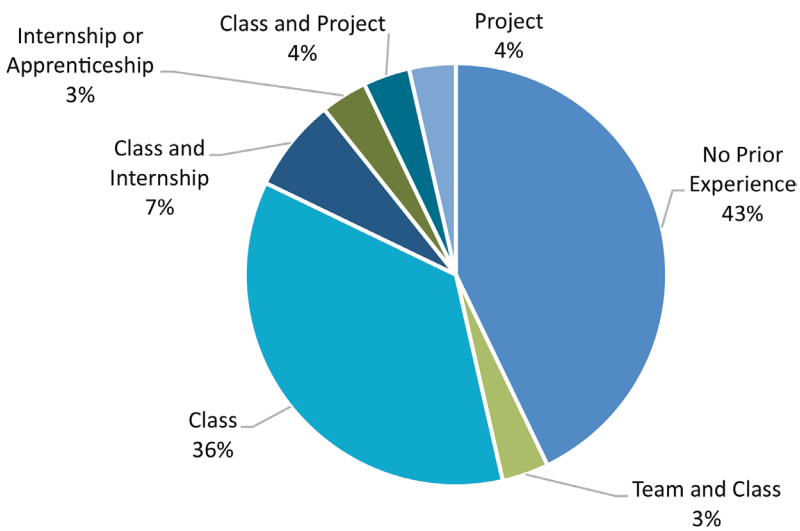


Figure 13. Prior GD&T experience breakdown for participants.

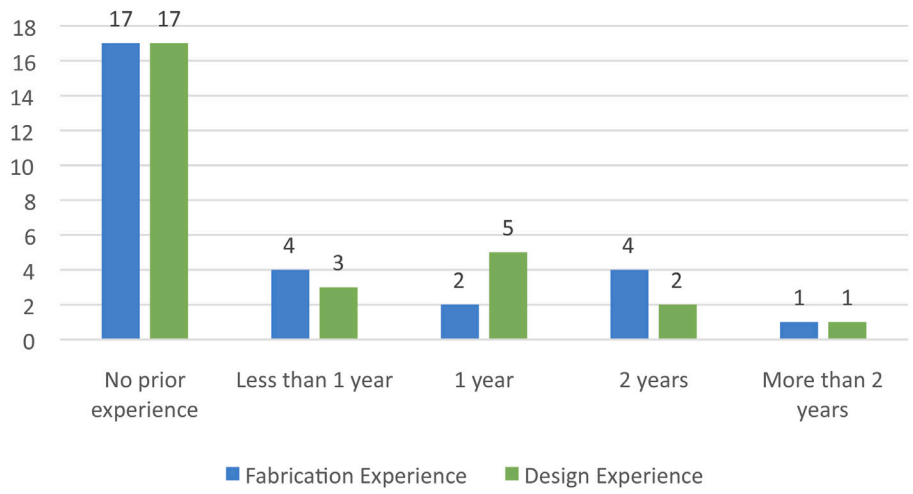


Figure 14. Years of fabrication and design-related experience of the participants.

fabrication and design experience. The other participants had a combination of outside projects, internship experience, team experience, and research. Figure 15 breaks down the experience of those who reported theirs.

Self-Efficacy

The averages of the scores were computed for each self-efficacy task before and after the intervention activities were given. Figure 16 shows the comparison of averages for all 15 tasks. All tasks

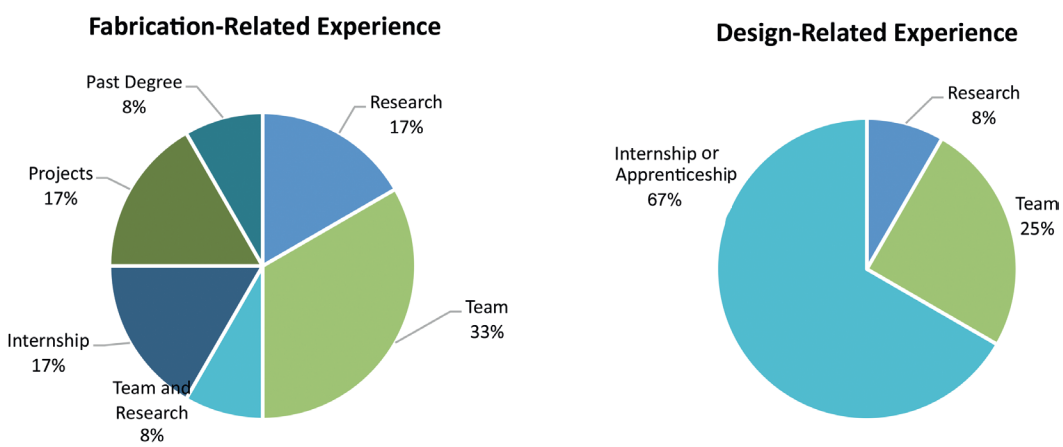
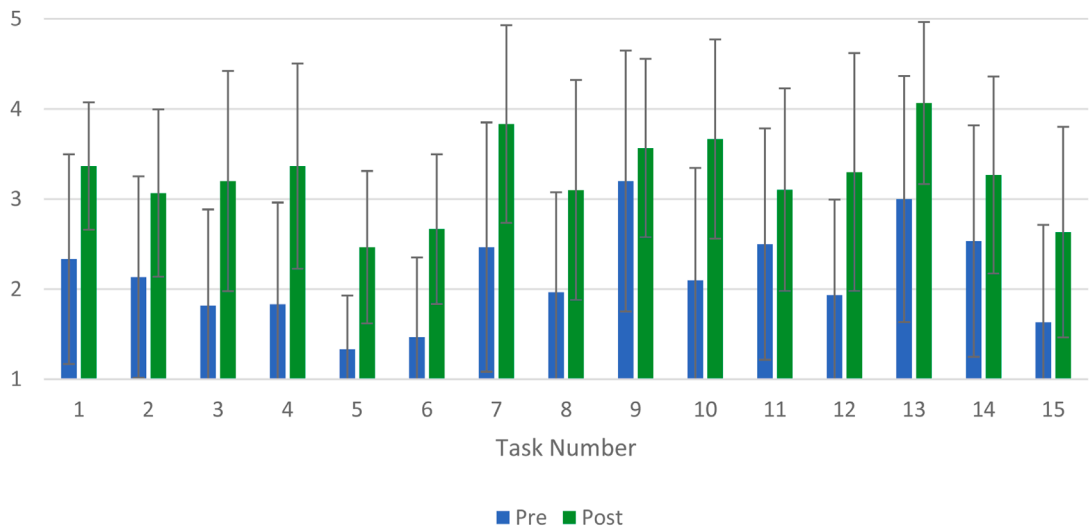


Figure 15. Breakdown of fabrication-related (left) and design-related (right) experience of the participants.



1. Identify Geometric Dimensioning & Tolerancing (GD&T) symbols
2. Choose correct reference datum based on part description
3. Calculate Least Material Condition (LMC) of specific hole
4. Calculate Maximum Material Condition (MMC) of specific hole
5. Create a Feature Control Frame (FCF)
6. Interpret a Feature Control Frame (FCF)
7. Measure the flatness of a feature using horizontal dial indicator
8. Measure the perpendicularity of a hole using gauge pin and dial indicator
9. Measure hole position using calipers and machinist square
10. Measure a hole size using go/no-go gauge pins
11. Measure a hole position using a gauge pin calipers and a machinist square
12. Verify the position of features relative to each other using functional gauge
13. Accept or reject features based on measurements conducted
14. Use a manufacturing method to decide the tolerance of a hole
15. Understand how to set up a part in a CMM (Coordinate Measuring Machine)

Figure 16. Average pre- and post- self-efficacy rating with standard deviation based on students' self-reported confidence; Error bars show ± one standard deviation.

had at least a 1-point change in average except task 9, which had a 0.4-point change and task 11, which had a 0.6-point change.

A Sign test was chosen to analyze pre- and post- Self-Efficacy responses. Due to the ordinal nature of the Self-Efficacy survey, the pre- and post-scores are matched pairs; each data set is of a non-normal distribution, but the symmetry of the differences are not the same. The test was used to understand the significance of the total groups' change in average Self-Efficacy. The Sign test

showed that the intervention activities did elicit a significant statistical (p<0.05) change for all Self-Efficacy tasks, except task 9 (p=0.481). For task 9, due to time, most students were not able to complete the inspection of the hole position(s).

Knowledge Assessment Results

The identical Pre-Intervention Knowledge Assessment and Post-Intervention Knowledge Assessment were administered before and after the intervention. The total possible score for the assessments was 29.5 points. The overall average Pre-Intervention Knowledge Assessment score was 7.42±4.30 points , and the overall average Post-Intervention Knowledge Assessment score was 16.18±5.69 points.

Due to the data being continuous and matched pairs with no significant outliers, paired t-tests were conducted to compare the Pre- and Post-Intervention Knowledge Assessment scores. The paired t-tests were run by total points possible for the overall score, as well as each assessment question.

Table 2 shows the breakdown of the paired t-test results with the average scores and standard deviation of each. Due to the means of the overall Pre- and Post-Intervention Knowledge Assessment scores, and the direction of the t-value (t(28)=–12.321, p<0.001), it can be concluded that there was a statistically significant improvement of the Post-Intervention Knowledge Assessment following the activities. There was a statistically significant difference (p<0.05) in the means comparison of each individual question besides Question 3 (t(28)=–0.972, p=0.339), which focused on Material Modifiers, and Question 6 (t(28)=–1.609, p=0.119), which focused on the difference between parallelism and flatness.

Table 2. Paired Samples t-tests comparing Pre-Assessment and Post-Assessment Scores.

	Pre-Assessment		Post Assessment				
Paired Question (Total Points)	**Mean**	**Standard Deviation**	**Mean**	**Standard Deviation**	**df**	**t**	**p**
Overall Score (29.5pts)	7.42	4.30	16.18	5.69	28	-12.321	0.000**
Question 1 (8pts)	2.41	2.18	5.45	1.55	28	-6.318	0.000**
Question 2 (7pts)	2.31	0.97	4.62	1.45	28	-8.068	0.000**
Question 3 (2pts)	0.97	0.87	1.24	0.95	28	-0.972	0.339
Question 4 (6.5pts)	1.16	1.40	2.57	1.43	28	-5.945	0.000**
Question 5 (3pts)	0.10	0.41	1.34	1.11	28	-7.008	0.000**
Question 6 (1pt)	0.40	0.43	0.55	0.45	28	-1.609	0.119
Question 7 (1pt)	0.10	0.31	0.34	0.48	28	-2.985	0.006*
Question 8 (1pt)	0.22	0.34	0.62	0.48	28	-2.213	0.035*

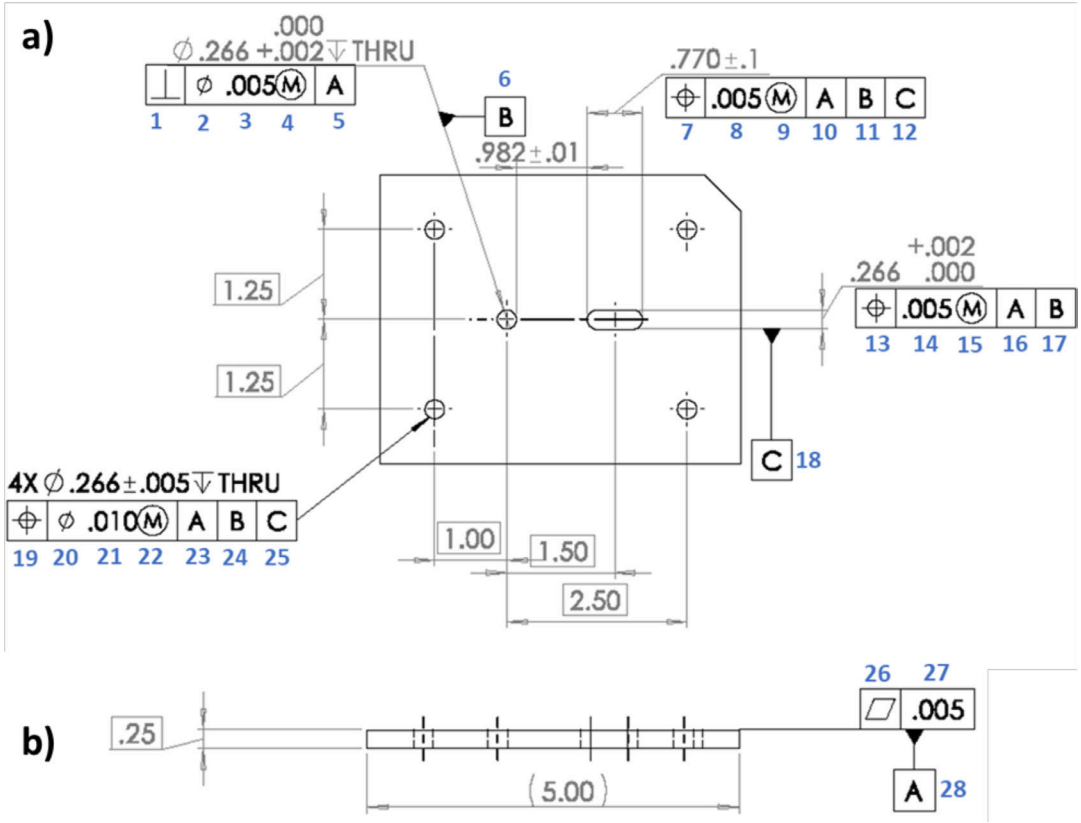


Figure 17. Activity part drawing solution of a) top view and b) front view with the labeled sections.

Part Drawings

In the intervention, Activity 1 consisted of a fill-in-the-blank style part drawing of the part the students were given, similar to the Knowledge Assessment part drawing. There were 28 blanks for the students to fill out. Figure 17 shows the solution and the labeled 28 blanks for the part drawings the students were given.

The 28 blanks were categorized into eight different topic sections. These topic sections and their corresponding blanks are summarized in Table 3. There were four topics where more than 40% of students could identify the specific blanks associated with Dimension (50.3%), Datum Callouts (41.4%), Datum Labels (48.3%), and Flatness (55.2%). The other four topics the students were not as strong in identifying the necessary characteristic callout on the Activity 1 drawing.

Table 3. Breakdown of 8 distinct topics and their corresponding blanks on Figure 17.

Topic	Related Blanks
Perpendicularity	1
Diameter	2, 20
Dimension	3, 8, 14, 21, 27
Material Condition	4, 9, 15, 22
Datum Callouts	5, 10, 11, 12, 16, 17, 23, 24, 25
Datum Labels	6, 18, 28
Position	7, 13, 19
Flatness	26

Exit Survey

The students were given an exit survey at the end of the intervention. The survey asked the students 5-point Likert scale questions and three open response questions. Five of the questions asked the students to agree or disagree (1 – strongly disagree and 5 – strongly agree) to if the activities contributed to the students' knowledge, and the sixth question asked the students to rate the usefulness of the overall intervention. Figure 18 shows the students' responses to the first five questions. The students mostly agreed the activities contributed to their understanding of GD&T, where Activity 1 (Part Drawing) was more beneficial than Activity 2 (Inspection Plan). More than half the students strongly agreed that the activities improved their knowledge of the topic. No students disagreed with the statements.

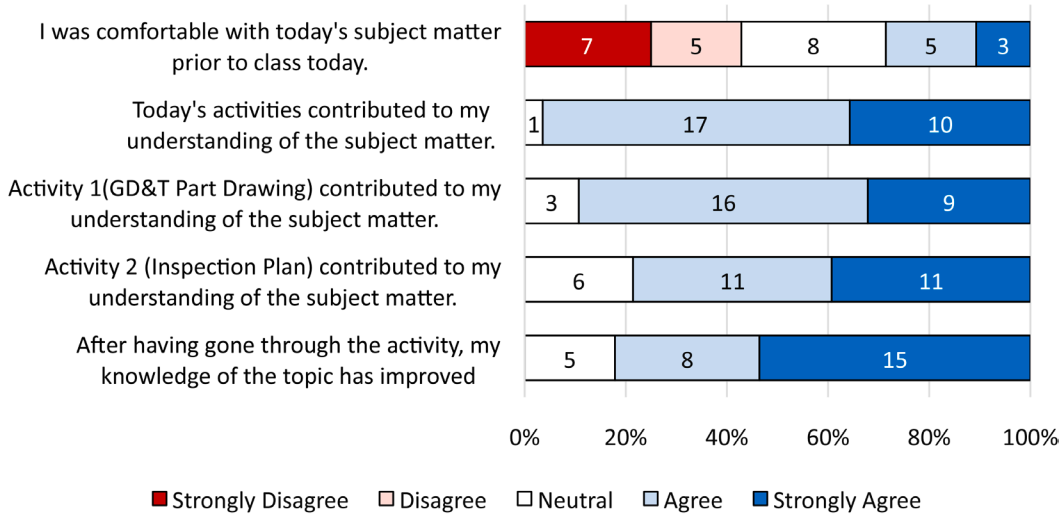


Figure 18. Exit Survey Responses.

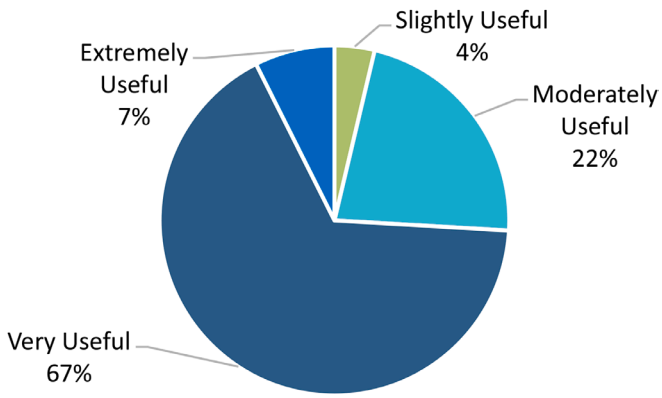


Figure 19. Distribution of the rated usefulness of the activities completed by the students.

The final question for the exit survey asked the students to give an overall rating in terms of the intervention's usefulness for learning and/or understanding of the subject matter. The ratings the students were given were: Not useful at all, Slightly useful, Moderately Useful, Very Useful, Extremely Useful. No student rated the module "Not useful at all," 65% of the students believed that the activities were "Very Useful," and 8% of the students deemed the activities "Extremely Useful." The distribution of the rated usefulness shown in Figure 19 shows that over 70% of the students deemed the activities completed were either Very Useful or Extremely Useful.

Perceived Value Survey

The perceived value survey asked students about components that were essential to the intervention, and students indicated whether they saw value in those components. The survey is broken into two distinct parts: the role of the student and the role of the instructor. The statements "I gave the activity minimal effort" and "I rushed through the activity" were reverse coded during statistical analysis to ensure the high value of "5" was the same for every statement due to the statements being negatively worded. Regarding the role of the student, the majority of the students completely agreed they saw the value in working with a partner for the activity. Also, half of students completely agreed they saw value in working with the inspection tools and the machined parts. The distribution of the survey answers is shown in Figure 20.

Exit Survey and Perceived Value Survey

Kendall's Tau-b correlation was run to understand the relationship between the self-reported responses on the Exit Survey and the Perceived Value survey. The data met the assumptions that it is

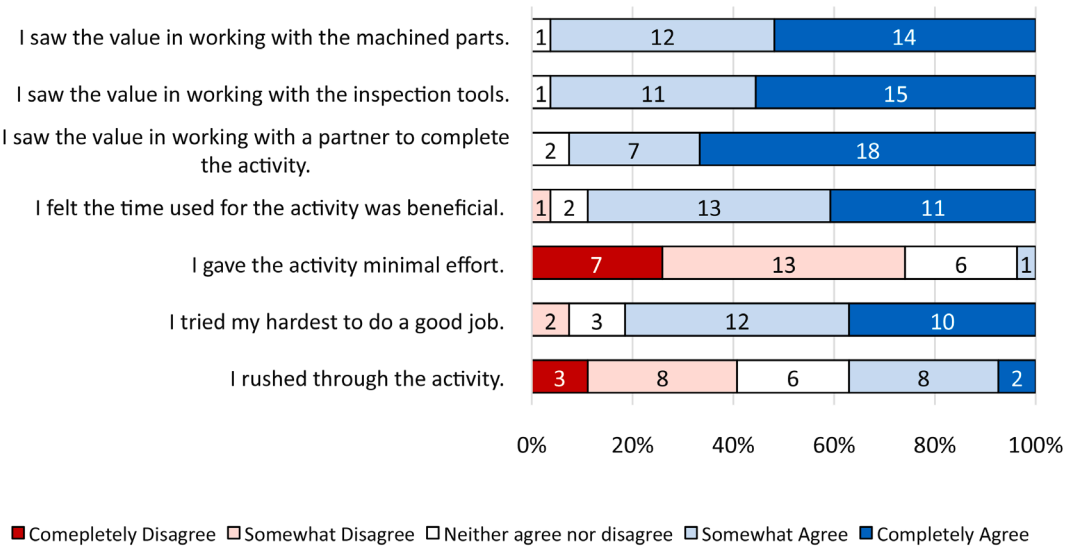


Figure 20. Perceived value survey answers in regard to the role of the students, the activity parts and their effort given.

ordinal and there is a monotonic relationship between the Exit Survey responses and the Perceived Value responses. Out of 40 possible correlations, four significant correlations resulted ($p<0.05$). No correlations resulted from the students' perception of the instructors' role in the intervention. There was a strong, positive correlation between the activities contributing to the students' understanding of GD&T and the students not giving the activity minimal effort (τ_b=0.433, p= 0.017). There was a strong, positive correlation between the students reporting that their knowledge of the topic has improved after going through the activity and the three following perception survey prompts: the students not giving the activity minimal effort (τ_b =0.414, p= 0.018); the students reporting "I tried my hardest to do a good job" (τ_b =0.354, p= 0.044); and the students seeing the value in working with the inspection tools (τ_b =0.447, p=0.015). These results revealed the students who gave effort to the activities also gained a sense of understanding of the topic of GD&T. Interestingly, the students who found value in working with the inspection tools noted the activities increased their knowledgebase in GD&T.

Self-Efficacy and Knowledge Assessment Scores

Kendall's Tau-b correlation was run to determine the relationship between 29 students' overall change in self-efficacy and difference in the total Pre- and Post-Intervention Knowledge Assessments. The assumptions the data met were that is the data is ordinal or continuous and there is a

monotonic relationship between the pairs of data. Similar to the self-efficacy difference calculation, the percent change (Post-Pre) in the Pre- and Post-Intervention Knowledge Assessments total scores were calculated. Out of 15 possible correlations, one significant correlation resulted. There was a strong, positive correlation between students' confidence in measuring the flatness of a feature using the horizontal dial indicator and the percent difference in the assessment scores (τ_b=0.359, p=0.012). The results from the comparison of the Self-Efficacy and Knowledge Assessment scores shows there is no direct correlation between the self-efficacy of the students and their performance on the assessments.

Self-Efficacy and Perceived Value Survey

Kendall's Tau-b correlation was run to understand the relationship between 29 students' overall change in self-efficacy and their perceived value of the intervention given and the instructors' role. This test was appropriate due to the monotonic relationship between pairs of ordinal data. Out of 165, seven significant correlations were found – three in regard to students' perception and four regarding the instructors' role. There was a strong, positive correlation between the students' confidence in calculating the maximum material condition (MMC) of a specific hole and them admitting that they tried their hardest to do a good job (τ_b =0.362, p=0.032). This association shows that the students trying their hardest with the activity allowed them to understand how to calculate the MMC of a hole. The two other associations were strong, negative correlations between the students rushing through the activity and their confidence to choose the correct reference datum based on part description (τ_b = –0.3309, p=0.042) and their confidence to understand how to set up a part in a CMM (τ_b= –0.426, p=0.009). The students' self-reported abilities and their lack of rushing through the activity were correlated for the identification self-efficacy prompts. These associations show that the students who did not rush through the activity were likely to set up a CMM and identify the datums based on given information.

Knowledge Assessment Scores and Exit Survey Results

Kendall's Tau-b correlation was run to determine the relationship between 29 student's Exit Survey responses and the percent scored on the Pre- and Post-Intervention Knowledge Assessments, and % in change in assessment scores. This test was appropriate due to the monotonic relationship between pairs of ordinal or continuous data. Out of 15 correlations, one significant correlation resulted. There was a strong, positive correlation between the students' Pre-Intervention Knowledge Assessments score and how comfortable they were with the subject matter prior to class (τ_b =0.290, p=0.048). This association shows the students who were previously comfortable with the material were able to perform better on the intervention activities.

DISCUSSION

The activities were beneficial to the students' learning of GD&T and informative to help the instructors understand how the students were impacted. This section discusses the significance of the student feedback received through surveys and how the students faired during the intervention.

Student Feedback

The Exit Survey was insightful feedback to help the researchers understand how the students felt they were impacted by the activities in the intervention. The majority of the students agreed that the intervention contributed to their understanding of GD&T, but six students were neutral about the intervention's contributions. Activity 1 was more impactful than Activity 2, but the students reported the intervention contributed to their understanding of the subject matter and their knowledge of GD&T had improved.

In regard to the perception survey, all students, except one, saw value in working with the machined parts and the inspection tools.. This shows that the students benefit from physical parts and hands-on learning that help students visualize their work (Rios 2018). Rios conducted a similar experiment using 3D printed parts to help students understand tolerances, considering material modifier conditions, and why they matter (Rios 2018). Over 67% of the students saw value in working with the 3D printed parts. They also saw the value in working with a partner to complete the inspection activities. This result reveals the students may have benefited from sharing their materials and discussing the inspection methods with each other in Activity 2. One can conclude that hands-on learning with GD&T specifically, allows students to have a deeper understanding of the concepts being taught.

Intervention Activities

There was an overall significant change in the student performance on their Pre- and Post-Intervention Knowledge Assessment scores. This can be attributed to a successful overall implementation of the intervention components. Although there was not a significant change between the scores of two questions in the Knowledge Assessment, it can be concluded that there was possibly an impact on the students' knowledgebase in GD&T. Question 3 was a multiple-choice answer question asking the students to accept or reject characteristics based on the information given. The students performed well on this, possibly due to the question only having two answer choices per specification. Similarly, the students did not have a distinct change in their scores from pre to post for Question 6, which asked about the difference between parallelism and flatness. Interestingly, many students had the same score or had a negative change in score from Pre- and Post-Intervention Knowledge Assessment, which implies the intervention may have confused the students in their understanding in the difference between parallelism and flatness.

Regarding Activity 1: Part Drawing portion of the intervention, less than 40% of students could successfully identify the information associated with the perpendicularity, diameter, material condition, and position categories on the part drawing for this activity. For perpendicularity, the students struggled to understand where to put the characteristic symbol or did not do it at all. For diameter, although it is a simple symbol, the students possibly did not grasp that holes and slots both have diameters and these were the focus of this part drawing; thus, these key concepts could be emphasized better. Additionally, focusing on the feature control frame and its elements is important. The lecture briefly went over the feature control frame and its characteristics, but emphasized the elements, such as the diameter symbol, the tolerance, and the material modifier for the tolerance. These are as important as understanding and calling out datums. Branoff used the student performance to understand the key missed concepts and similarly, practice was needed for identifying features with size and defining how tolerances get applied when specifying a basic dimension (Branoff 2018b). Although he ran a whole course with multiple deliverables, one can see that students possibly have the same problems with understanding certain GD&T concepts.

Regarding Activity 2: Measuring Activity, the students were not able to complete one of the most extensive, but most important parts of the activity – measuring hole position. This phenomenon was reflected in the self-efficacy survey analysis because the Task 9 statement asking the students' confidence to measure hole position with machinist square and calipers was the only statement that did not have a significant change in score. Although, the activity was at least two hours long, the students had to adjust to the different measuring tools and understand how to effectively use them. The hole position measuring activity consisted of many strenuous calculations and multiple tools needed in order to calculate the hole position. In the other inspection activities, the students were able to understand the use of the go no-go pins and functional gauge easily to accept or reject the parts. The problem lied in the first measuring activity: Inspect Flatness. The students had problems reading and translating the dial indicator measurements to paper. Also, the setup of the dial indicator was slightly complicated, and the instructors had to assist the students in the set up for many of the groups. Even though these misunderstandings occurred in both classes, the students nonetheless expressed the activities' positive impact on their knowledge and confidence in GD&T.

LIMITATIONS

Development of an active learning intervention to help the students learn a specific complex topic in mechanical engineering comes with its shortfalls. The limitations of this study stem from

this project being a newly implemented active learning intervention based on Geometric Dimensioning and Tolerancing. The limitations are in both the developmental phase and implementation phase of the intervention.

In the current state of industry, GD&T is done by a CMM, and manual inspection methods are lesser known and expensive. The intervention was developed as a lower cost (<$300/pp) intervention in which key inspection steps are taken to help measure features of a part. For high-tech inspection methods, such as the CMM, variable costs are incorporated into the usage bill, and they are used in large manufacturing facilities. This makes the cost of accessibility of the inspection machinery out of reach.

For implementation, there is not a control data set because the class in which the topic is taught does not have a previously designated unit for GD&T. Although there is not a designated unit, GD&T is a topic that is needed for use throughout the entire mechanical engineering curriculum at Georgia Tech and beyond. There is not a distinct way to conduct a controlled study about what is taught in GD&T. Another limitation of this study is the lack of iterative development that will be able to be done with the activities. This is the only semester the study was run, and the data cannot shed any light on longitudinal effects of the intervention on students' ability to communicate with GD&T throughout their tenure at Georgia Tech.

During the creation of the intervention, the ideal scenario would be for the students to use partnered learning to inspect both Part A and Part B, instead of only Part B. One partner would be responsible for each inspection protocol. Unfortunately, due to the COVID-19 pandemic and school space and class rules, there was not a feasible way for people to be partnered and for the students to work on two parts. The decision to work only on Part B was based on the more diverse inspection methods that a student would be exposed to during the activity.

For the results, there was a small sample size (n=29) of participants. Ideally, this intervention would have been completed in all of the lab sections of ME2110. The limitation to the small sample size is the possibility of students believing their comprehension of the topic improved, although it may not have. In regard to timing, another limitation is the intervention time did not allow for the students to complete all of the inspection steps that were set forth in the activities. The students either rushed through the position of a hole method or did not complete it at all.

In terms of expanding the intervention in the future to be more complete, it would be beneficial to discuss the history of GD&T, associated standards, its evolution and variation in industry over time. In addition, during the discussion of the use of datums, more content on tolerance stack up and its implications would help students gain a better understanding of the importance of datums and how error can build across a part or assembly.

CONCLUSION AND FUTURE WORK

In this paper, the topic of GD&T in the undergraduate curriculum and its incorporation into a classroom was addressed. The development process of an active learning activity using machined parts and group learning was described to help the reader see the importance of selecting topics useful to those students who will potentially utilize GD&T in the future. Creating activities that allow students to conduct manual measurements instead of using a CMM to inspect parts helps bridge the gap in knowledge between the part drawing and the actual part. Student performance metrics were obtained through a Knowledge Assessment and a Self-Efficacy Assessment, and those results were analyzed. The evaluation of the metrics revealed that the activities had a positive impact on the students based on both assessments. This gives hope that the future iterations and implementations of the GD&T intervention activities will have an increased positive impact.

The development and implementation of active learning modules in GD&T have been used in entire classes, but in this paper, the intervention was conducted during a single lab section of the students. This topic is unique because it involves students referencing materials in order to complete the activities and come to a conclusive decision:, whether or not a part is in spec. The following strategies for implementation are based on an active learning intervention that allows the participants to inspect and make decisions based on measurements.

1. **Develop clearer, more concise instructions.** This will reduce the ambiguity and give the students more time to do their work instead of trying to figure out what to do.
2. **Develop videos or diagrams that students can access to help set up the inspection tools.** Videos or intuitive diagrams that will help the students assemble inspection set ups or any similar set ups will decrease the time the student spends on set up and increase the time students work with the parts.
3. **Work with the students closely** instead of sitting and waiting for them to have a question. This helps the students want to give their best to the activities they are working on when the instructors are working with them.
4. When developing inspection methods, **pick the two or three most common and most important inspection activities** that will give the students a substantial time to experience the hands-on activity and comprehend the reasons the activity is relevant. There is a substantial benefit to students to have a specific experience with two or three activities where the information is fully comprehended, instead of having multiple inspection activities that students rush through and do not grasp what is trying to be taught.
5. Implement the activities at a time in the curriculum **when the students have had a baseline exposure to GD&T**. If the students do not have exposure to GD&T built into the curriculum,

take 2-3 class periods to implement the lecture and the inspection activities. Breaking the exposure of GD&T down to the lecture for one class period and the inspection activities for the other day(s) will alleviate the time pressures and allow the students to converse and learn more about the manual inspection methods through practice instead of theory.

Future work consists of developing a more concrete intervention structure that will be easily transferable between classes or lab sections. Although two lab sections did have the experience of these GD&T activities, there were issues that arose and were corrected before the second lab section. Creating a better timing schedule and a more robust set of inspection methods that are less confusing will be beneficial for effective future implementations. Testing to see if the students benefit more from completing a part drawing after the inspection activities instead of before (as done in this intervention) is an area of interest. Implementing this intervention into the ME2110 lab section for methods training would be the overarching goal. Another aspect of future work is following students for the remainder of their undergraduate years after the intervention to understand if the knowledge was retained and helpful, if the knowledge was used for internships, in class or capstone projects, or during personal fabrication projects.

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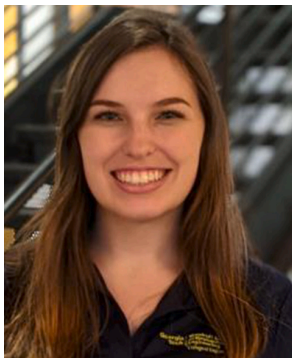

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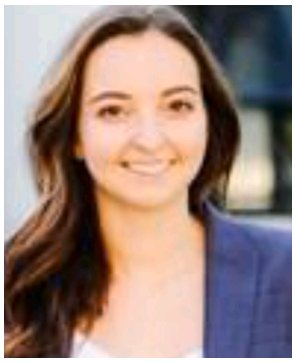

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