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# A Hands-On Approach to Teaching Tolerancing and Design for Manufacturing: Designing and 3D Printing Precision Puzzles and a Visor Connector

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# A Hands-On Approach to Teaching Tolerancing and Design for Manufacturing: Designing and 3D Printing Precision Puzzles and a Visor Connector

Abstract:

Mechanical engineering freshmen level students with no machining experience at Washington State University lack the understanding of geometric dimensioning and tolerancing which affects the quality of their engineering drawings in the Engineering Computer Aided Design and Visualization course. An innovative pedagogical approach is being developed to address this issue and give students an opportunity to learn the concept and practical application of GD&T through a hands-on, design-based group project. The first project required them to design, model in SolidWorks, and 3D print four interlocking puzzle pieces; the second project involved students designing, modeling, and 3D printing a replacement bracket for a car visor. Both projects required precise geometric tolerance to function correctly. Analysis of tolerance and fit using 3D printed parts allowed students to learn from the tangible results of their designs. This approach was anticipated to help students' understanding of dimension variation, and geometric control in creating functional assemblies. Initial assessment was done in Spring 2024 semester. Preliminary assessment indicates that this approach will have a positive impact on their understanding of tolerancing and design for manufacturing.

Introduction:

Freshmen level Mechanical Engineering students at Washington State University, Pullman lack machining experience when they take their first engineering class, Engineering Computer Aided Design and Visualization (ME 116). Without machining experience or exposure to the design process, it is difficult for students to construct knowledge [1] about the concept of dimensioning for manufacturing and the importance of tolerances when multiple parts are designed to connect. The puzzle project allows us to address the knowledge gap by introducing hands-on real-life learning. To complement the background of tolerancing and dimensioning learned by the puzzle project, another project was introduced where students would reverse engineer and 3D print a visor connector. While there are significant examples in the literature related to improvement of visualization in computer graphics or computer aided design class, teaching dimensioning in the context of manufacturing is rather limited especially for freshman level students with no exposure to machining concepts. Research related to teaching dimensioning with active learning in undergraduate engineering classes is discussed in various literatures. Project-based active learning was implemented in a freshman level Mechanical Engineering computer graphics class [2] in City College of New York and Borough of Manhattan Community College where students learn Engineering graphics with group projects. While Geometric dimensioning is taught for documentation purposes, tolerancing concept is taught using actual machine parts by showing examples with specific machining concepts. An interactive self-learning tool for manufacturing dimensioning is developed to teach dimensioning in the context of machining for freshman level students [3]. The self-learning tool developed in this work includes videos of machining to explain the manufacturing dimensioning.  Southwest Texas State University developed an experiment to allow students to apply concepts of GD&T learned in lecture. The study showed that their approach had a great impact on students' learning process and retention of the concepts [4]. When a model building technique was integrated into a Theory of Machine class, it contributed to a major improvement in students' learning process to understand the mechanisms and concepts of motion [5]. The effectiveness of teaching GD&T with 3D printed parts in a CAD class in University of Texas at Dallas was demonstrated in [6]. To give students a better understanding of context of dimensioning with machining videos was demonstrated in [7].

Dimensioning and tolerancing teaching:

The motivation for improving curriculum to address knowledge gaps about the concept of 'fit' and dimensioning for manufacturing came from the experience of teaching senior level design courses, ABET assessment, and concern received from alumni. Typically, students learn hands on tolerancing concept in junior level Manufacturing class 'ME 312'. Students' performance in upper-level design courses where they design and build a product showed poor performance in producing engineering drawings for fabrication. These knowledge gaps require repeated iterations before the final product can be manufactured, which causes manufacturing delays.

Project outline:

The puzzle project was developed in Spring of 2024. In this project, Students were asked to design a set of 4 puzzle pieces.  The design had to be self-explanatory with pieces that fit snugly, are easy to assemble and disassemble by hand without using any tool and are suitable for a 5-year-old child to play with. Also, it had to remain held together when picked up. To accomplish that, students created SolidWorks parts, assembly, and engineering drawings with appropriate clearances to make their parts fit snugly together. Then all models were 3D printed using PLA, and students tested the 3D printed parts for 'fit'. For puzzles that did not fit together or were too loose, students did a reflection on their design problem. The team size was 2. The size limit for each piece is 1" x 1" x ½", not including the connector geometry. The blocks can be connected in various ways. The connector pieces that link the blocks together must all have uniquely different geometry. One must be round or elliptical, one must be triangular, and the other(s) that they choose, must be different. The project outcome was assessed, and some improvements were incorporated in Fall 2024. For Fall '24, students were given the option to choose between PLA or TPU materials for their 3D printed puzzle. To give students a better understanding of 'fit' and 'clearance,' necessary to produce a satisfactory puzzle, 3D printed peg and hole gauges shown in Fig. 1 were provided to the students in both PLA and TPU materials . An online source [8] about the different types of fit with 3D printed parts were also shared. Some sample puzzles designed by the class are shown in Fig. 2. As part of the puzzle project, students were also taught the meaning of tolerance—how to select appropriate tolerances, how to indicate tolerances on a drawing, and how to inspect parts to ensure compliance with specified tolerances.

In addition to submitting their part files for 3D printing, students also submitted part drawings for each puzzle piece with tolerances specified for the connector geometries. A pair of sample student drawings is shown in Fig. 3. Since this was their first introduction to tolerances, they were not required to apply dimensions and tolerances to their entire part—just the connecting features. Students chose the nominal dimensions based on their interactions with the hole/peg gauges to determine the typical clearance needed between connecting pieces. The tolerances for these features were then selected by evaluating how much deviation from these dimensions could still result in a proper fit. Some students used unilateral tolerances and others used symmetrical tolerances. After printing their puzzle pieces, the students were asked to inspect their pieces using calipers to measure the connecting features and check whether or not the dimensions fell within the tolerance zone they specified in their drawing. They were then instructed on how a manufacturer would respond if they discovered a part that didn't meet tolerance specifications.

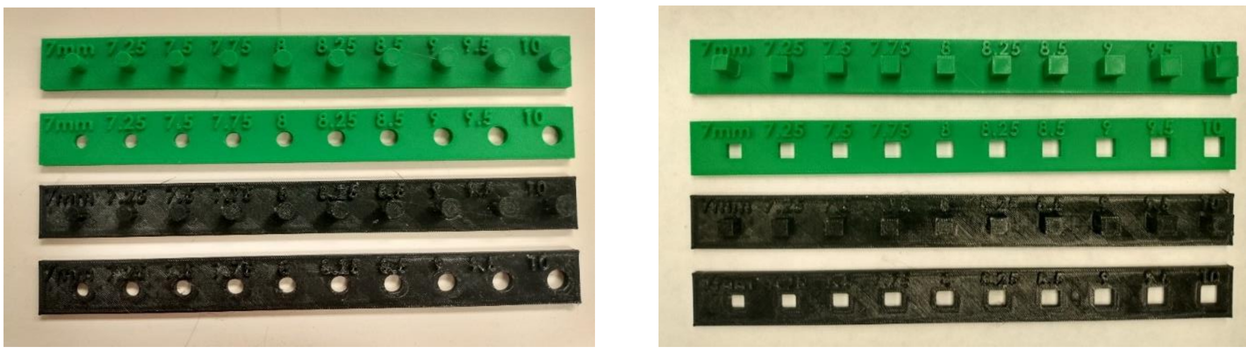

Figure 1: 3D Printed Peg and Hole gauges

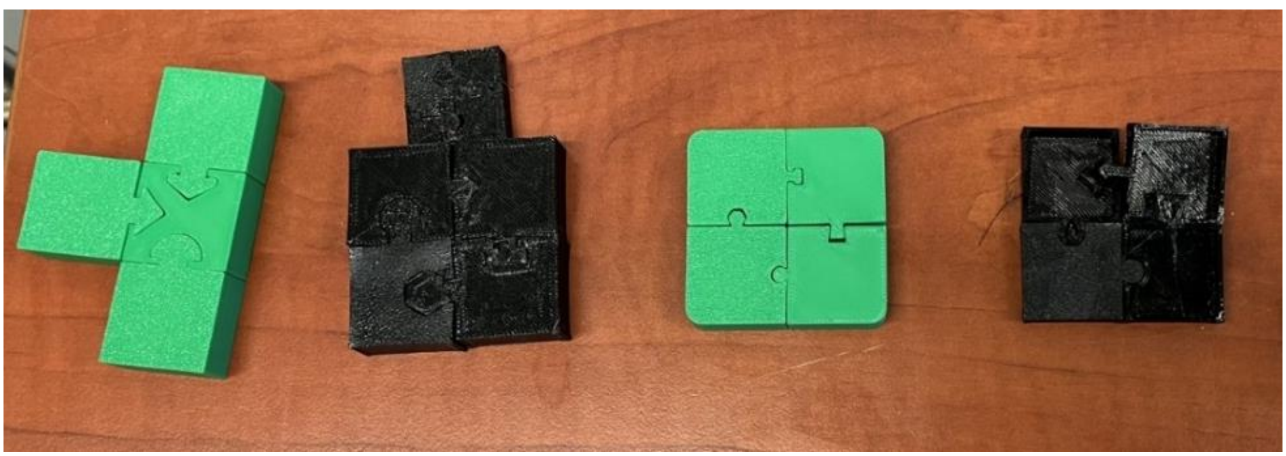
Figure 2: Examples of 3D printed puzzles designed by students

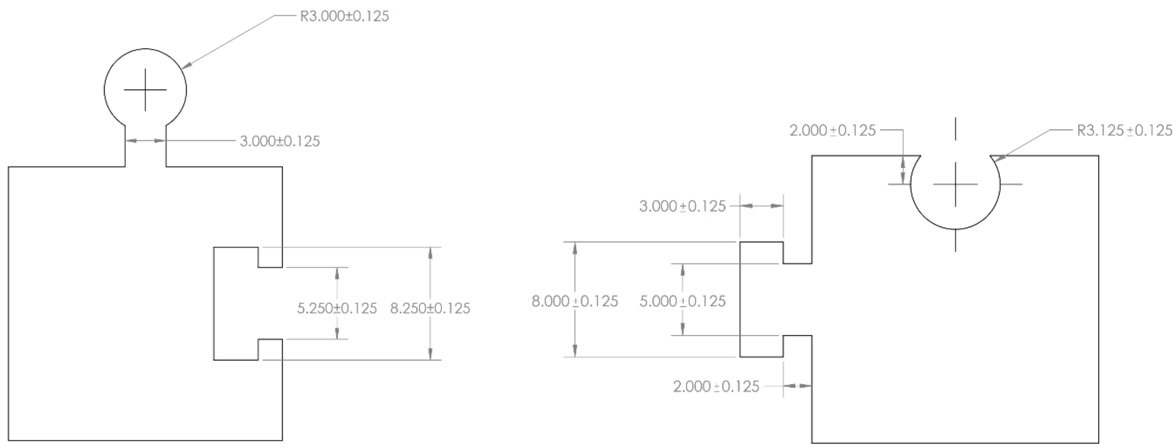

Figure 3: Examples of student part drawings for puzzle project

To further solidify their background about the concept, another project was added in the Fall 2024 semester where students designed, and 3D printed a replacement car visor bracket as shown in Figs. 4-6. The purpose of this project was to help them further understand the concepts of ‘fit’ and ‘clearance.’ Their replacement bracket could mimic the original design or look completely different, but it had to meet requirements for intended functionality: the bracket had to hold the visor securely in the two positions (stowed horizontally, deployed vertically) without any visible sagging, should work with the existing mounting holes/fasteners, and should maintain stiffness after 5 cycles of stowing/deploying the visor. Students were also given the option to use a 3D scanner for reverse engineering the original bracket. The 3D scanned visor part is shown in fig 7. 62% of students used scanned visor to reverse engineer the part in SolidWorks. 38% of students used calipers to measure the dimensions and created the part in SolidWorks.

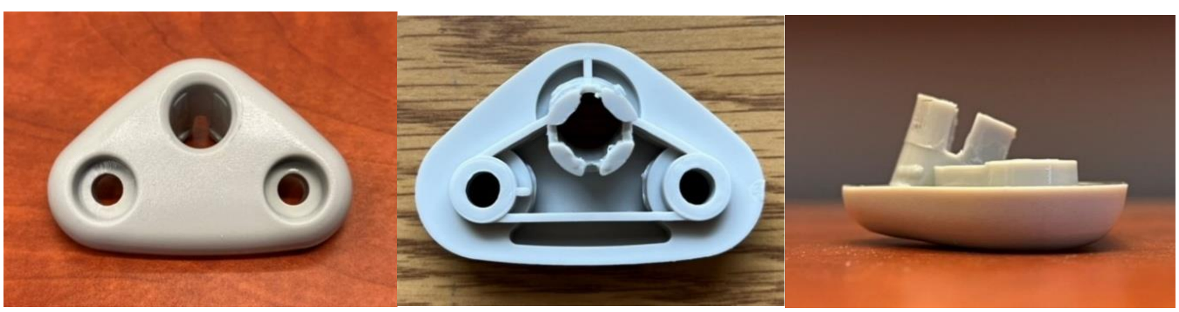
Figure 4: Real car visor part from Subaru Forester.

Figure 5: Visor bracket is shown in red circles.

Figure 6: 3D printed visor brackets designed by students

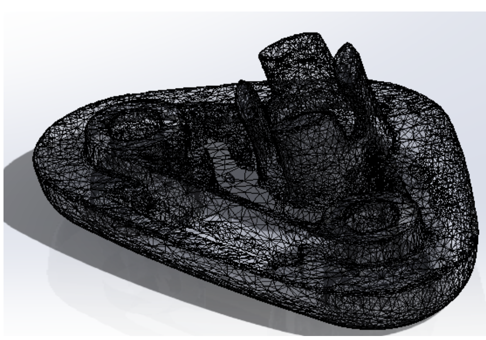

Figure 7: 3D scan of original visor connector.

Results:

We assessed the following research question: Did students understand dimension variation, design for manufacturing in creating functional assemblies?

Project 1: Puzzle

Students inspected their printed puzzle pieces by evaluating ‘fit’ and measuring the connector features with calipers to determine whether their printed parts satisfied the tolerances they had specified on their part drawings. If the students’ parts did not fit together, they were given the opportunity to earn points back by submitting a reflection, commenting on how they would modify their design to ensure tolerances would be met and pieces would fit together.

In the Spring 2024 semester, when only PLA material was allowed, 38% of the student puzzles fit snugly together while 62% were either too tight or too loose to hold together properly. In the Fall 2024 and Spring 2025 semesters, when the choice between PLA and TPU materials was provided, 59% and 41% of the student puzzles fit snugly together on the first attempt.

| **Semester** | **Material Choice** | | **Quality of Fit** | |
|---|---|---|---|---|
| | **PLA** | **TPU** | **Snug Fit** | **Too Tight/Loose** |
| Spring 2024 | 100% | - | 38% | 62% |
| Fall 2024 | 39% | 61% | 59% | 41% |
| Spring 2025 (first attempt) | 48% | 52% | 41% | 59% |
| Spring 2025 (after revision) | 75% | 25% | 100% | 0% |

Table 1: Puzzle project outcome data

The reason for this slight improvement in puzzle outcomes can be attributed to two changes that were implemented in the Fall 2024 semester: (1) students were provided with 3D printed hole/peg gauges in Fig 1 to help them size their connectors for an appropriate fit, and (2) students were given the option to print their puzzle pieces out of PLA or TPU. PLA is a hard plastic, but TPU is soft and flexible. Puzzles printed with TPU can be flexed to fit with neighboring pieces while PLA pieces require much more precise tolerancing. Although allowing students to use TPU makes it easier for them to achieve a snug fit, improper design still results in deformation of the pieces and was considered an improper fit with associated point deduction. The addition of the TPU material option gave students the added experience of material selection to meet specific design requirements.

In 2024, the students who submitted a reflection on their puzzle design mentioned their knowledge gap related to ‘fit’. They discussed how they would adjust the dimensions to accommodate better fit. Overall, this project gave students a first introduction to 3D printing, tolerancing, and design for manufacturing.

In 2025, students were given the opportunity to modify their design after testing their initial 3D printed puzzle to correct for 3D printing imperfections and ensure tolerances would be met. The performance of their revised 3D printed puzzle pieces showed a huge improvement as attached in Table 1.

Project 2: Car visor connector

For the visor bracket project, students again had the opportunity to choose between PLA and TPU materials. Reproducing the visor bracket using 3D printing is a challenging feat as it requires a tight, snap-in fit to keep the visor from falling out of the bracket. This type of fit is difficult to achieve with rigid materials like PLA which are prone to breaking when the visor is inserted. It is easier to achieve this type of snap-in fit with flexible materials like TPU, but these materials struggle to support the cantilevered weight of the visor without significant sagging. Thus, simply mimicking the original injection-molded design with these materials would not produce a functional bracket. Students had to design their brackets and carefully adjust clearances to account for the shortcomings of whatever material they selected.

| **Semester** | **Material Choice** | | | | **Quality of Bracket** | |
|---|---|---|---|---|---|---|
| | **PLA** | **TPU** | **Both** | **2 Pcs** | **Screws Fit** | **Proper Angle** |
| Fall 2024 | 29% | 71% | 0% | 29% | 87% | 18% |
| Spring 2025 (initial attempt) | 34% | 48% | 17% | 24% | 90% | 17% |
| Spring 2025 (second attempt) | 31% | 38% | 31% | 38% | 100% | 46% |

Table 2: Visor project outcome data

Most students chose to design their bracket as a single piece, using either PLA or TPU. Some students chose to create a 2-part bracket design using an interlocking design or a reinforcement ring made out of the same material or a different material than the base structure. Common problems that were observed from the visor project: PLA brackets were too tight and would break when the visor was inserted, TPU brackets were too loose and not stiff enough to hold the visor at the appropriate angle. Students had to be creative with their designs to account for the shortcomings of each material option. Using an additional ring sometimes helped but it did not work for every team that designed the ring. Most students succeeded with hole sizing and spacing for mounting hardware. In Spring 2025, students were given an option to revise their design and reprint it after testing their initial design for fit and functionality. The students' revised bracket designs performed significantly better, overall, than their initial attempt, as shown in Table 2. This opportunity to revise and improve their design helped expose students to the iterative nature of the design process and the importance of early prototyping and testing.

Overall, students seemed to enjoy the hands-on projects as an opportunity to see their designs come to life. A survey given to the students following the puzzle and visor bracket projects in the Fall 2024 semester revealed that only 52% of students had used a 3D printer prior to taking the class, and only 10% had used a 3D scanner before. As seen in Fig 8, students also felt that the two hands-on projects were particularly helpful for improving their understanding of reverse engineering, design for manufacturing, and the importance of proper tolerancing. Students also indicated that the hands-on projects made them significantly more excited to study engineering. Several students commented in the survey that they appreciated learning skills they could use in the real world and valued seeing and testing how the tangible result differed from their CAD design.

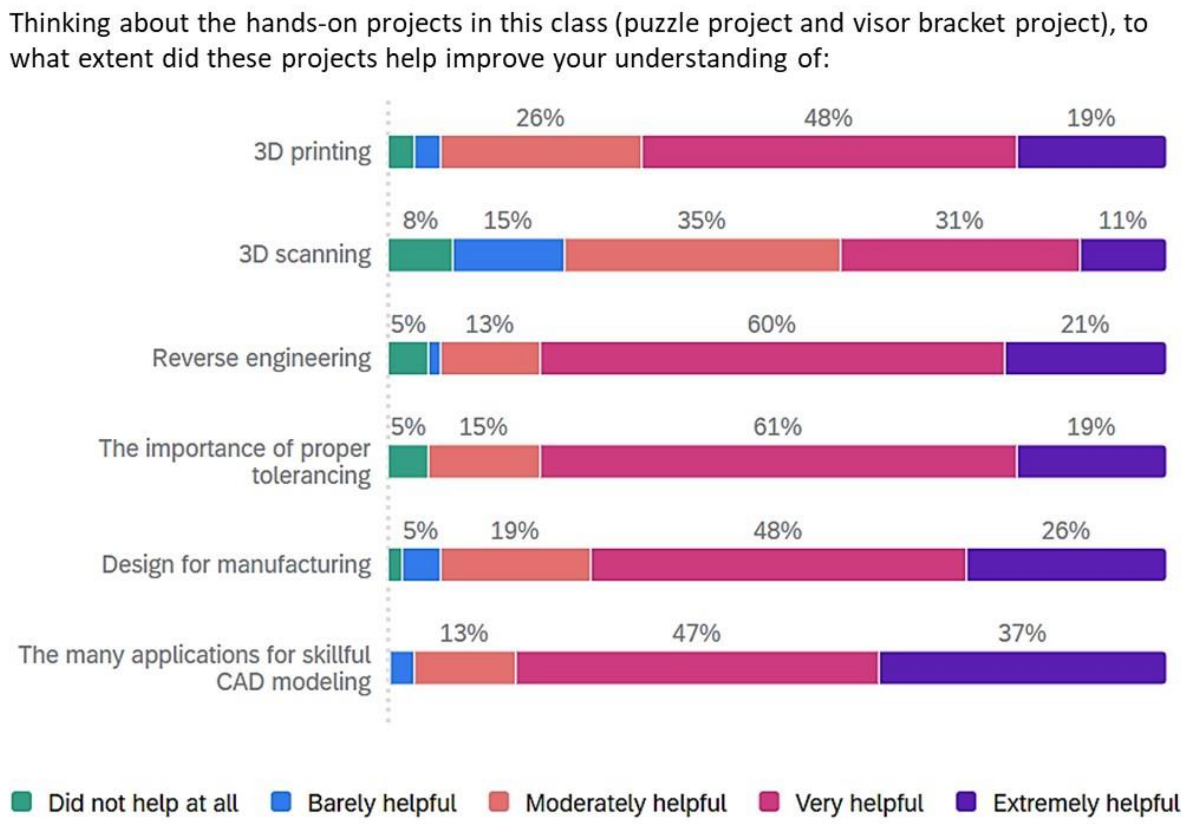

Figure 8: Student's response of one survey question

Students learned several key concepts from these hands-on projects in ME 116 by realizing and evaluating the tangible outcomes of their CAD designs:

1. Not every CAD design can be easily manufactured; intended manufacturing methods must be considered when designing parts.
2. Parts that fit together in CAD may not fit together when manufactured; interlocking pieces must be carefully designed with appropriate clearances and tolerances to account for manufacturing imperfections.
3. Appropriate tolerancing is highly dependent on the intended manufacturing methods and material selections.

Conclusion and Future plans:

These projects did provide students with a helpful reality check when they recognized the imperfections associated with manufacturing, the timeline for these projects did not allow enough time for students to iterate and improve their designs after the initial printing/testing in 2024 when this work started but in 2025, schedule was adjusted to accommodate a revision from students and reprint.Students  tweaked and reprinted their designs after testing and inspecting their initial manufactured parts.

The preliminary results are promising. The impacts on students learning can be seen in the survey data where a big group of students found that projects were helpful to understand the importance of tolerancing and design for manufacturing. The material choice advantage/disadvantage is a good angle to improve. TPU works better for the puzzle but worse for the visor. Many students failed to account for the shortcomings of the materials they selected. It would be interesting to know why, or how to better have students reflect on this before they do the projects to consider the pros/cons. In future, we will continue to improve the project after assessing the outcomes. We will further investigate the type of material that we use for the 3D printing, assessing the pros and cons. After we improve these projects fully, we plan to incorporate a different fabrication process for the puzzle and visor to show students the importance of understanding the manufacturing process when they select a specific material for their product.