Utilizing a CMM in a Capstone Design Project to Learn Manufacturing Quality Concepts

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Abstract
Purdue Polytechnic Columbus employs a two-semester, capstone design project to provide senior-level students a team-oriented, project experience common to manufacturing enterprises. The project simulates the interaction between an original-equipment manufacturer (OEM) and a potential supplier. The OEM is represented by a 4-person team from Purdue Polytechnic Columbus (PPC) and the supplier is represented by a 4-person team from Purdue Polytechnic Anderson (PPA). Each of the teams communicated regularly with representatives from a manufacturer near the respective campuses. Included on each student team were roles corresponding to a team leader, a design engineer, a purchasing engineer, and a quality engineer. This work focuses on the role of the quality engineer utilizing CMM results to evaluate the quality of the manufactured product. The quality engineers on both teams performed CMM measurements on critical dimensions and characteristics of the manufactured parts. These measurements from the supplier and the OEM are compared as they used different brands of CMM and different processes to perform the measurements. Ultimately, these measurements are utilized to drive the Production Part Approval Process (PPAP) and inform the OEM and the supplier about the capability of the supplier.

Learning Objectives
The learning objectives for this paper are summarized below:

1. Learn how a university capstone-design class incorporated a Coordinate Measuring Machine to create a productive assignment integrating measurement and quality concepts.
2. Demonstrate how the class linked measurement and quality to the overall product lifecycle process for a supplier and an Original Equipment Manufacturer (OEM).
3. Discuss a possible one-page lab report format utilizing proper terminology for a succinct and direct document.

1. Introduction

Several years ago, Purdue Polytechnic Columbus desired to upgrade its teaching and learning methods to a more modern, active, and student-centered style. While Purdue Polytechnic Columbus always had emphasized applied learning more than theory learning and included many hands-on activities in the classes, some improvements were needed to transform the educational experience to the 21st century. There are 10 elements to this transformation:

1. Theory-based Applied Learning
2. Team Project-based Learning
3. Modernized Lecture Methods
4. Integrated Learning-in-Context Curriculum
5. Integrated Humanities Studies
6. Competency Credentialing
7. Senior Capstone Projects
8. Internships
9. Global/Cultural Immersions
10. Faculty-to-Student Mentorship

These 10 elements are being integrated into 4-yr Bachelor of Science degree programs throughout Purdue Polytechnic Columbus but, clearly, utilizing all 10 in a single class is not possible. This work focuses on Senior Capstone Projects, which is defined by Purdue Polytechnic Columbus as:

- Senior Capstone Projects – Two-semester projects require teams of seniors to apply everything they have learned to solve industry challenges for real clients.

2. Capstone Project Defined

A group of academics, industrial employees, and consultants earned a pilot project award from the Indiana Defense Network entitled “Pilot Demonstration of Universal Digital Thread Framework for Learning, Agility, and Workforce Development.” As the title suggests, learning and workforce development are part of the objectives for the project and the two-semester, senior capstone class was determined to be the most effective way for the project team to investigate learning and develop suitable training/learning programs to support the project goals.

The larger project objectives involved interaction between an original equipment manufacturer (OEM) and a supplier that is designated a small-to-medium manufacturer (SMM). The companies in this case are Cummins, Inc., a global power manufacturer in Indiana, and Mursix Corporation, a custom components manufacturer in Indiana. Due to geographic circumstances, a senior capstone team at PPC and a senior capstone team at PPA were engaged to execute a product-development scenario for the project, integrating communication protocols from both enterprises to define the digital thread framework.

In this scenario, the team at PPC served as the OEM, working closes with Cummins representatives to properly define and execute the product-development process from an OEM perspective. Likewise, the team at PPA served as the SMM, working closes with Mursix representatives to define and execute the product-development process from the perspective of a supplier or SMM.

3. Product-Development Scenario

The product-development scenario illustrates use of the Digital Thread across a product life cycle that involves both the OEM and the SMM. The following summary merely illustrates one type of scenario and is utilized for highlighting the potential efficiency gained by incorporating innovative digital thread features.

All the exchanges summarized below involve use of the “data wrapper” (configurable metadata) that travels with the information and the part across the life cycle. Such a scenario drawn from real experience includes potential for a design change, a reversion back to the original design, and a part failure under warranty after introduction to the market.

The product lifecycle simulation begins with the OEM selecting a part to outsource to a supplier. This part is an idler shaft insert and is illustrated in various views in Figure 1.

a. For the simulation, a group of 4 students from institution A represents the OEM and a group of 4 students from institution B represents the SMM. These two groups of students are registered in a two-semester capstone class at each location.
b. Each team will communicate frequently with employees of the two enterprises to learn about the product lifecycle process. However, all communication related to the production of the part will happen between the student groups and is meticulously cataloged by both teams in a single document. This tracking allows an extensive evaluation into the effectiveness of the communication and will identify avenues of improvement with the digital thread.

This part has been outsourced by the OEM for a number of years so drawings, standards, and processes from the OEM perspective are already established. The SMM is not the current supplier.

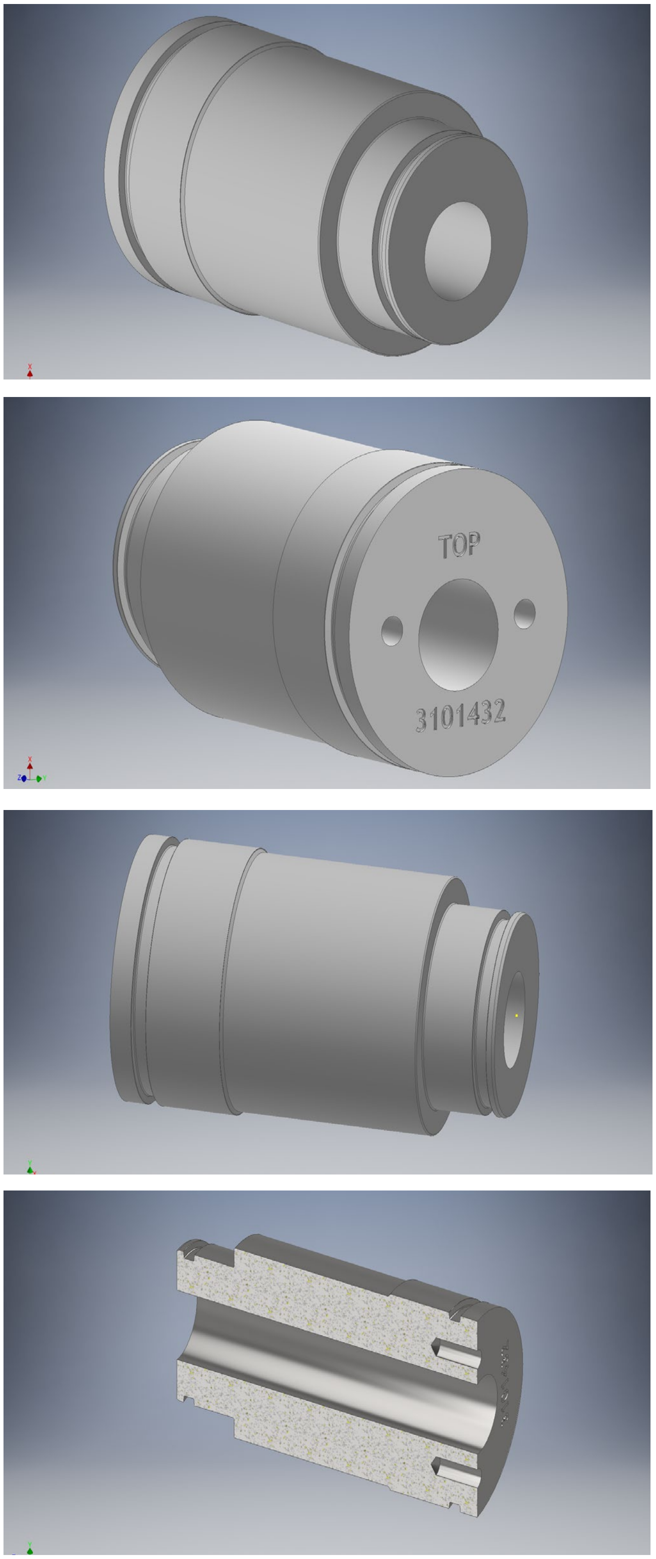

Figure 1.

Various views of the Idler Shaft Insert part used in the product lifecycle simulation.

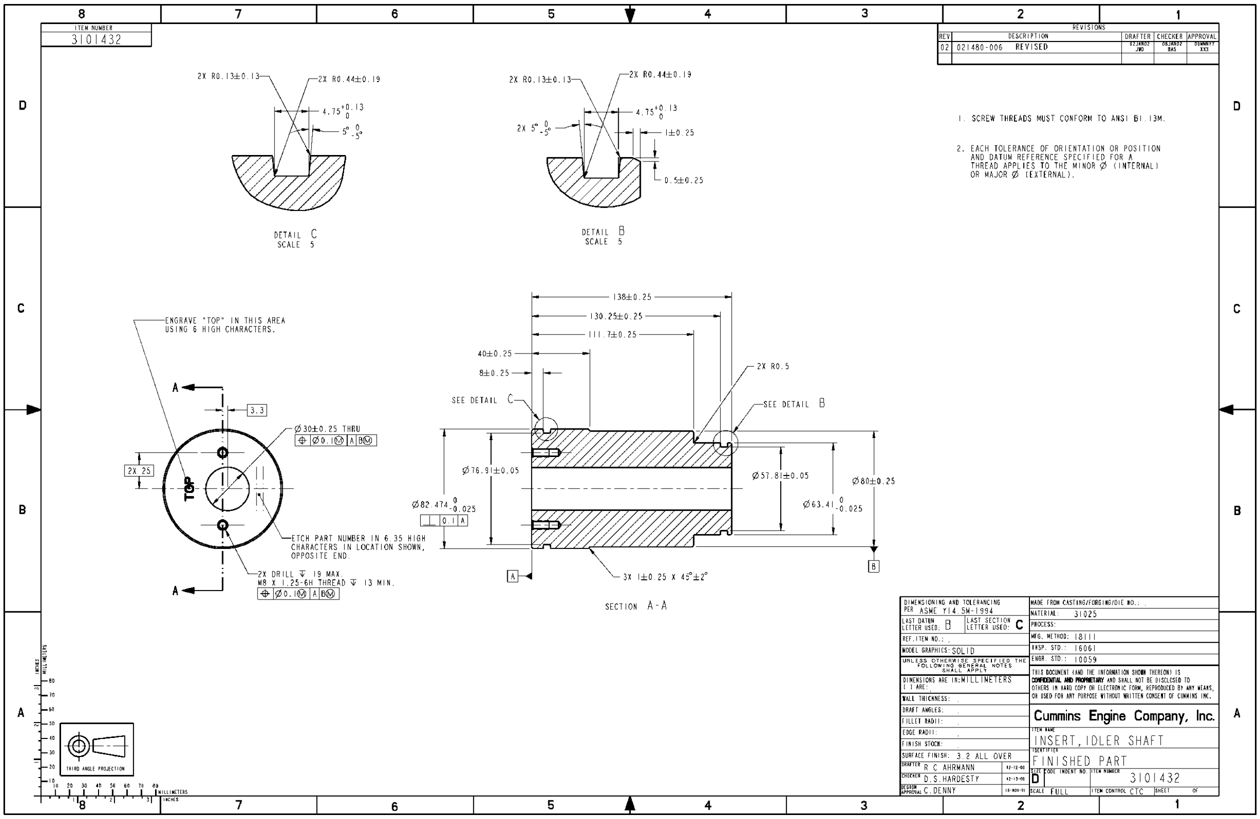

Figure 2. Dimensioned drawing of the idler shaft.

Timeline for Scenario begins in October, 2020.

1. OEM prepares Request For Quote (RFQ) for the idler shaft part and designates supplier(s) to receive the RFQ.
   Artifacts: ***Request for Quote (RFQ) (OEM)***
   System Product Requirements
   System Product Design
   System Performance Model
   Part Drawing
   Material Standards
   Inspection Standards
   Engineering Standards
   Consensus Standards
   Process Standards
   Capacity Study
2. OEM allows potential suppliers to provide 2 quotes if desired:
   a. The first quote asks suppliers to match the tolerances, materials, requirements, dimensions and overall features of the part as specified in the RFQ and system requirements artifacts.

   b. The second quote allows suppliers to modify some of the features in (a) to lower the overall price of manufacturing the part. This could include material changes, slight modifications of tolerances that could include geometric dimensioning and tolerancing specifications or surface finish specifications, and any other features of the part that would lower the price.
      Artifacts: ***Quotes for manufacturing part. (SMM)***
      Could include a second quote that modifies requirements to lower piece price.

3. OEM reviews quotes from suppliers to determine the optimal approach to manufacturing the part. This includes evaluation of all quotes received and determination if proposed changes in the quotes modified to achieve a lower price are acceptable.
   a. Includes communication among OEM team to determine if modifications are acceptable.
   b. Potentially includes communication with supplier(s) in an iterative approach to implement modifications or if only a subset of modifications is acceptable.

4. OEM selects SMM to manufacture 32 of the parts, which represents a short manufacturing run with limited quantity of the part. This limited quantity will play a large role in how the SMM dedicates resources to produce the part. OEM creates Purchase Order to begin manufacturing process.
      Artifacts: ***Purchase Order***
      Product Failure Modes & Effects Analysis (FMEA)
      Product GANTT Chart
5. SMM utilizes their resources to produce a prototype of the part utilizing subtractive manufacturing while simultaneously developing the process flow, the process Failure Mode and Effects Analysis (FMEA), and the production process control plan.
      Artifacts: ***Balloon Drawing***
      Process Flow Diagram (SMM)
      Process FMEA
      Production Process Control Plan

6. SMM sends the prototype part(s) to OEM for validation
   a. Validation of SMM capability regarding subtractive manufacturing and overall quality of the part. This includes
      i. Part geometry, dimension and tolerance inspection
      ii. Functional capability of the part in the intended product system
      iii. Cost information supporting commercial viability
      Artifacts: ***Product Test Results (OEM)***
      Dimensional Results (OEM and SMM)

Cumulative Costs

7. OEM issues PPAP (Production Part Approval Process) and releases that to SMM.
   Artifacts: ***PPAP Level III instructions from OEM***
   Signed Warrant (OEM)

8. SMM develops tools for PPAP.
   Artifacts: ***Qualified Laboratory Documentation***
   Validation of Fixtures/Gauges/Measurement Aids
   Measurement System Analysis (MSA)
   Process Capability Study
   Submission Package
   Supplier Packaging Approval
9. Collaboration – OEM inspects the part, analyzes the results and begins an iterative process with the SMM incorporating modifications (dimensional, material, manufacturing etc). SMM re-fabricates the part and sends to OEM to continue the validation process. This iterative process continues until both parties have agreed on part quality, manufacturing processes, and continuing work.

10. OEM gives SMM confirmation of part integrity and SMM moves to production.

    Artifacts: ***Check Sheets***
    SPC Charts
    Work Instructions
    Set-up Sheets
    Production GANTT Chart
11. At the OEM, responsibility is transitioned from product engineering to Product Life Cycle (PLM) management system
    Artifacts: ***Continuous Quality Improvement (CQI) Plan***
    Warranty Materials
12. The part is incorporated in the assembly and the engine is introduced into the market. A field failure launches an investigation using the Digital Thread to retrace the design and production history.
13. The investigation identifies errors, challenges, and improvements to augment the original design and manufacturing of the part with digital communication and digital transfer of data utilized efficiently.
14. This failure also provides an opportunity to highlight when in the cycle the SMM representatives requested data or asked questions and if the OEM provided the correct data and answers promptly and without much superfluous information. In other words, did the OEM provide the right data, at the right time, in the best manner available?
15. Post-simulation analysis will allow for discussion of the results and the lessons learned during the simulation. This includes the advantages

and disadvantages of using the digital thread and places where it might be used to effectively change the product life-cycle process.

4. Focus on PPAP – Scenario Steps 6-8

While there were many elements to the scenario above, the ones of particular interest for this work involve the quality tests related to the PPAP (Production Part Approval Process). In particular, measurements of both O-ring grooves are investigated in more detail due to their critical role in the function of the part. The idler shaft's main function is to plug a hole and provide a seal for the fluids used in the assembly of the engine and the two O-rings provide that seal. Contact pressure between the O-rings, the grooves, and the surrounding part is required to maintain the seal. Therefore, the outside and inside diameters of the groove as well as the width of the groove are critical dimensions for the operation of the O-ring and the idler shaft.

At institution A, a Zeiss Duramax (last calibrated 12/16/2020) coordinate measuring machine was utilized to perform the measurements of the two O-ring grooves. Additionally, the Zeiss machine is located in Purdue Polytechnic Columbus's measurement Center, which is environmentally controlled to 20 ℃ ± 0.5 ℃ with relative humidity lower than 50 %. These conditions are maintained at all times with preventive maintenance and inspection performed annually. The student team, with assistance from the lab manager, conducted the measurements using the Zeiss machine and the Calypso software. Thirty of the manufactured parts were measured in this fashion.

At the SMM, the measurements were obtained using a vision system and were converted from inches to millimeters and rounded to two decimal places. And, they were not performed in a controlled environment. From a quality perspective, these procedures raise several issues about the quality of the measurements. Only five of the parts were actually measured using these procedures.

5. Measurement Results

The relevant dimensions, shown in Figure 3, are as follows:

Ø82.474 +0/-0.025 mm

Ø76.9 ± 0.05 mm

Ø63.41 +0/-0.025 mm

Ø57.81 ± 0.05 mm

4.75 +0.13/-0 mm (width of O-ring grooves; shown in detail B and C)

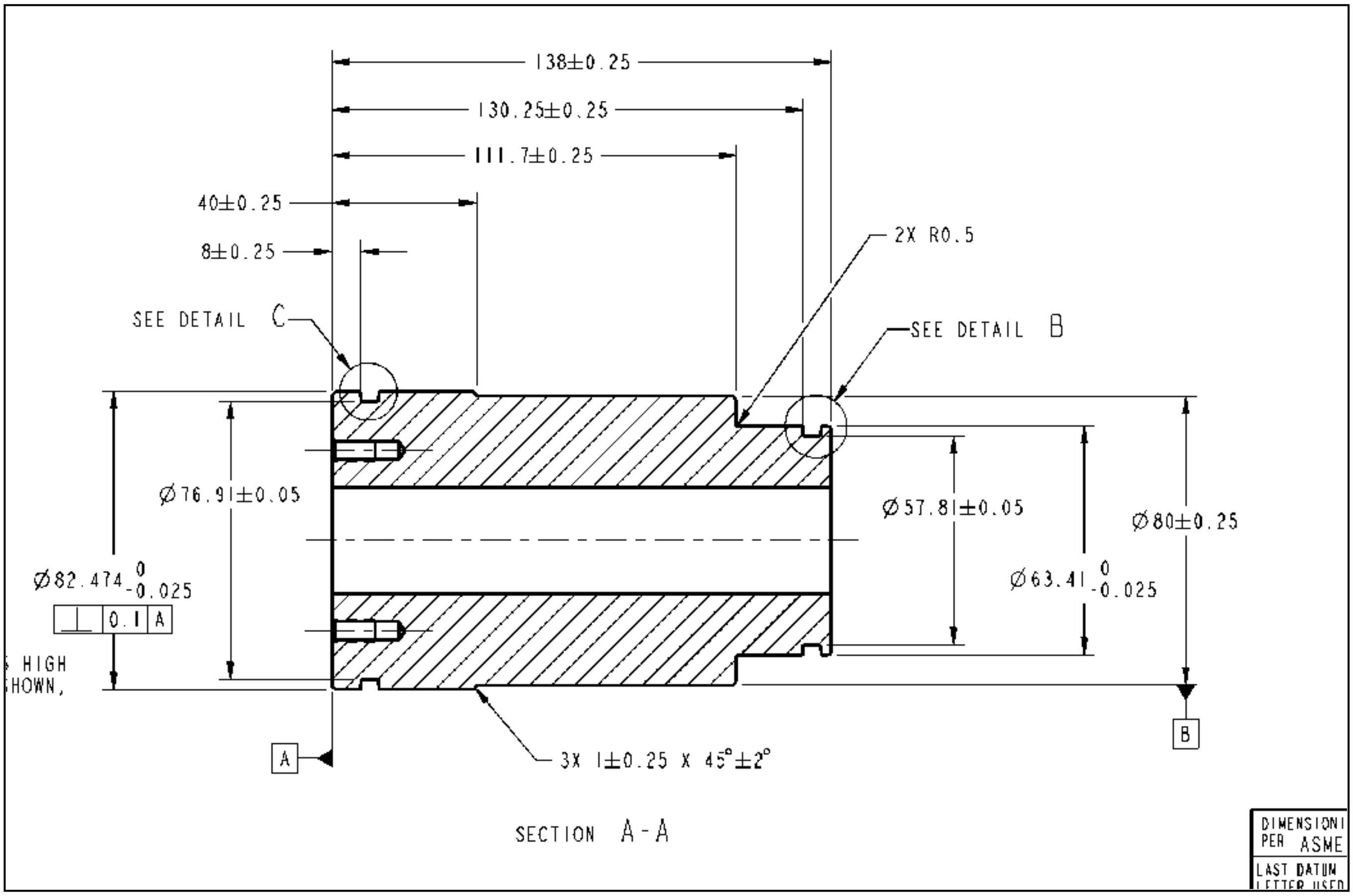

Figure 3. Blowup of the drawing showing the outer diameters and inner diameters of the two O-ring grooves that are paramount for the sealing function of the part.

Data for the outer diameter and inner diameter for the larger O-ring groove are shown in Figures 4 and 5. A single point is skewing the graph of the outer diameter; however, 20 of the 30 parts are out-of-tolerance. There is an interesting characteristic of the five SMM measurements that appear to be shifted slightly downward from the Purdue measurements, indicating a bias or offset in those measurements.

A similar shift is visible in the SMM measurements for the inner diameter of the large O-ring as seen in Figure 5, although a much larger percentage of the parts have inner diameters which fall between the tolerance limits.

Capstone students also performed CMM measurements on the outer and inner diameters of the smaller O-ring (Figures 6 and 7) and on the width of the two O-ring grooves (Figures 8 and 9), which are designed and manufactured with the same dimension and tolerance limits. Similar shifts in the SMM data are apparent in those sets of data as well, although the shifts are larger in some cases. It's interesting that the general trend of the comparisons is nearly the same in all 6 sets of data with the SMM data always being less than the PPC data. Additionally, notice that with the large O-ring outer diameter (Figure 4), that the OD of part 2 is greater than part 1 but that the OD of part 3 is less than part 1. Interestingly, the SMM data follows the same pattern and that this pattern is repeatable in the other 5 data sets. While there are several classes in the Mechanical Engineering Technology curriculum that utilize the CMM, this was the first time it was combined with manufacturing quality concepts.

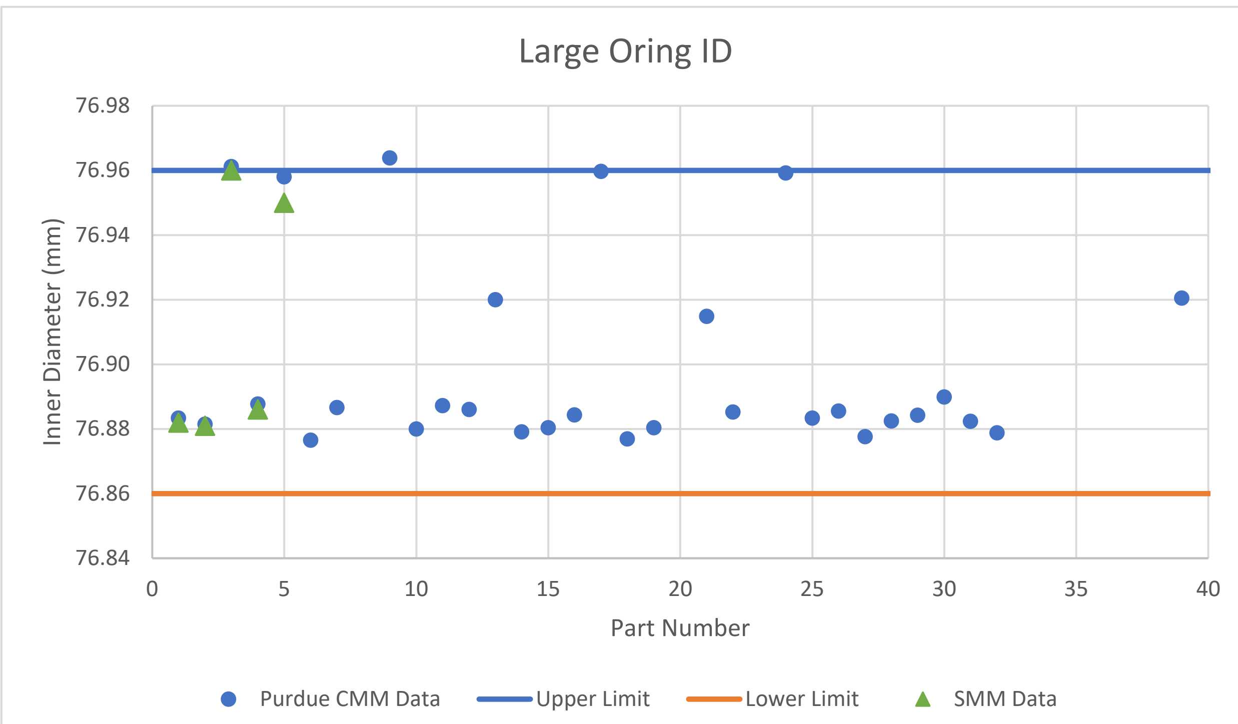

Figure 5. Graph displaying values of the inner diameter of the larger O-ring groove in the Idler Shaft. The two lines represent the upper and lower tolerance limits. SMM data are only for parts 1-5.

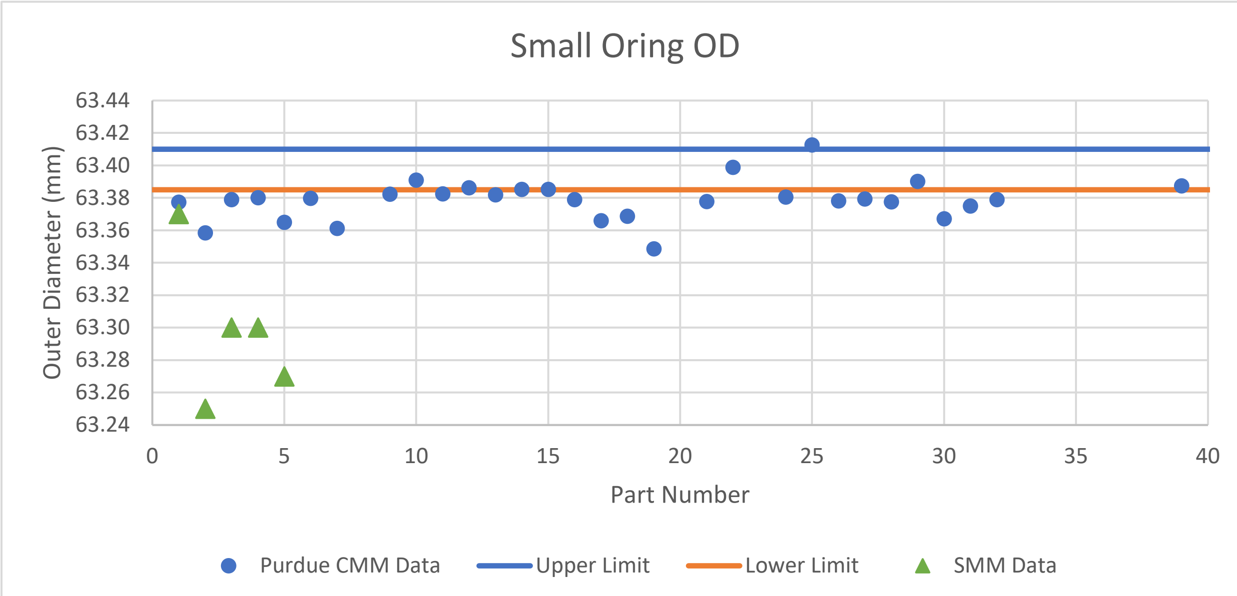

Figure 6. Graph displaying values of the outer diameter of the smaller O-ring groove in the Idler Shaft. The two lines represent the upper and lower tolerance limits. SMM data are only for parts 1-5.

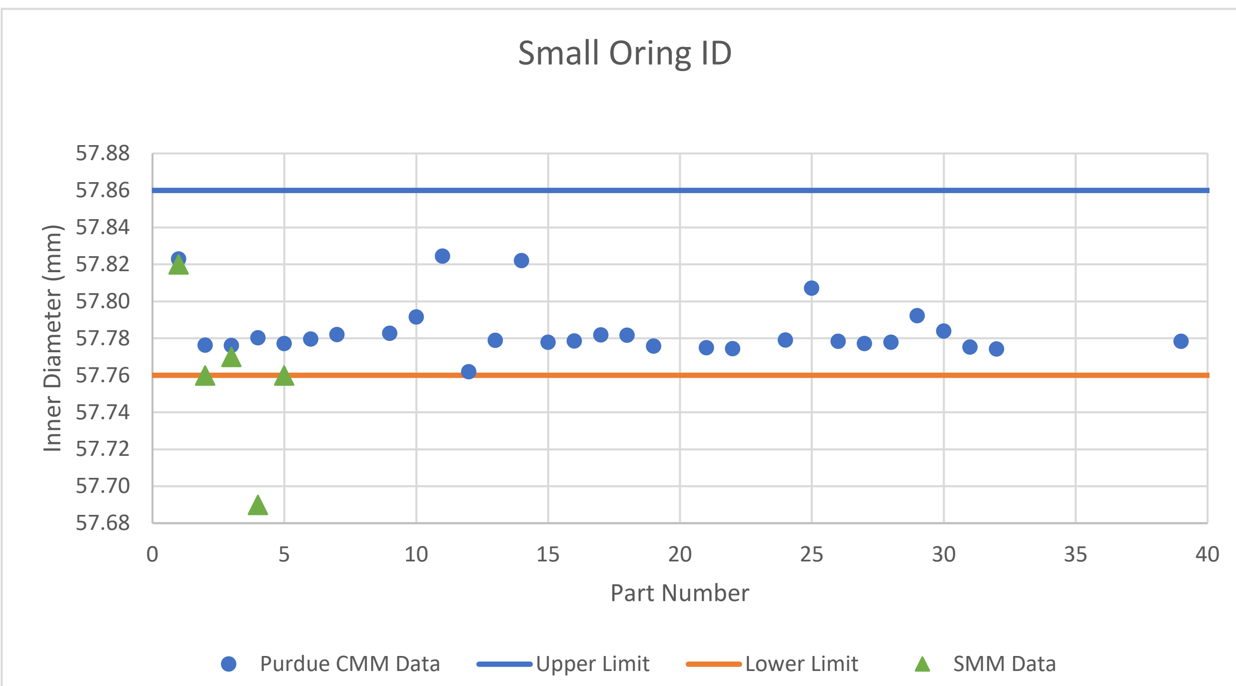

Figure 7. Graph displaying values of the inner diameter of the smaller O-ring groove in the Idler Shaft. The two lines represent the upper and lower tolerance limits. SMM data are only for parts 1-5.

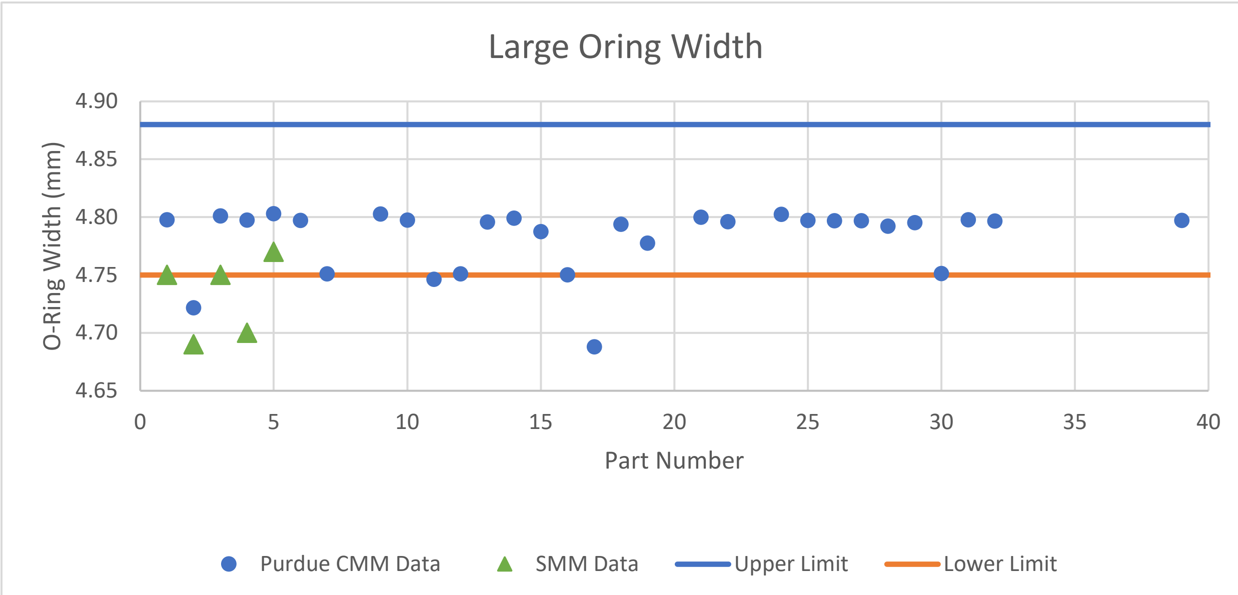

Figure 8. Graph displaying values of the width of the larger O-ring groove in the Idler Shaft. The two lines represent the upper and lower tolerance limits. SMM data are only for parts 1-5.

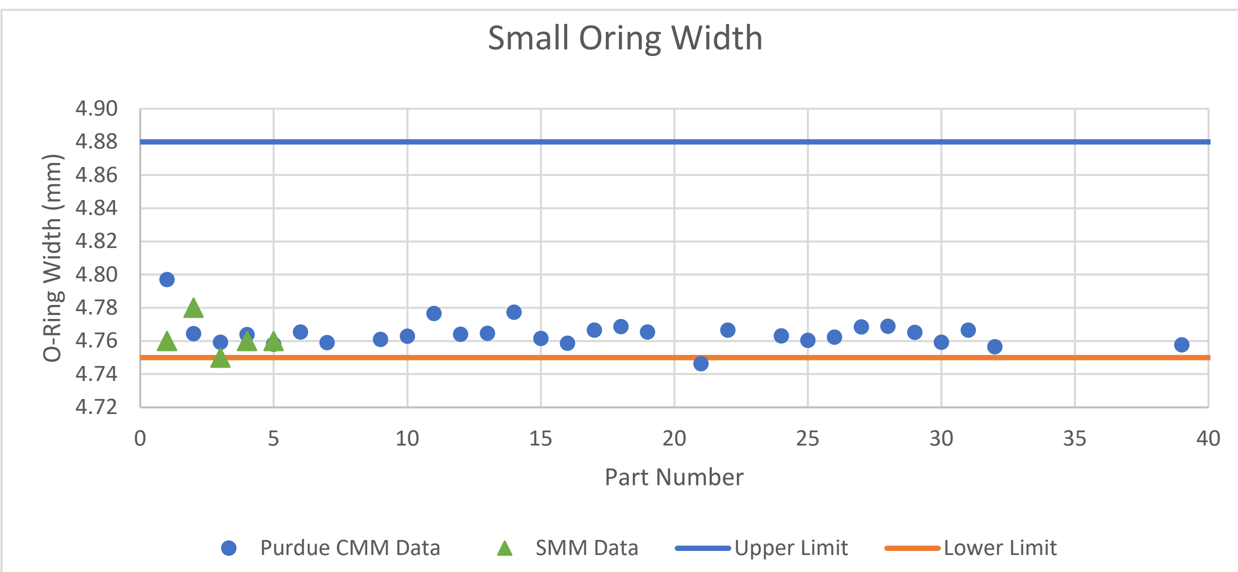

Figure 9. Graph displaying values of the width of the smaller O-ring groove in the Idler Shaft. The two lines represent the upper and lower tolerance limits. SMM data are only for parts 1-5.

There certainly are other interesting characteristics of the data. The two O-ring grooves are the same width and while the majority of measurements of the larger O-ring fall very close to the nominal value, the smaller O-ring data is clearly shifted toward the lower limit. It would be instructive to investigate why this difference exists and if it's acceptable. Most of the measurements are within the tolerance limits so those parts would likely be judged as good parts but there is some reason for the shift on the smaller O-ring.

5. Conclusions

This work describes a project for a Mechanical Engineering Technology capstone-design class that utilizes students' previous work with measurement and coordinate measuring machines to evaluate real manufactured parts and experience the OEM-supplier relationship, especially as related to quality and measurement. The focus of the assignment affects a couple of the transformation elements of Purdue Polytechnic Columbus – Capstone Design classes and Integrated Learning-in-Context, which is defined below:

- Integrated Learning-in-Context Curriculum - Learning *how* to do something by understanding *why* it is done, within the context of how it relates to other subject matters, ties courses together.

In many classes, students learn the "hows" of measurement, GD&T, and other manufacturing topics. The measurement of actual manufactured parts including the GD&T elements, bring together the "why" it is done as those activities address the manufacturability of the part and quality of the process. The "why" part answers the questions "does the part assemble properly" and "will it function as it is intended" in the assembly.
A significant part of the project included the interaction with the SMM, the supplier, as these measurement and quality issues surfaced. This type of learning experience is not one that engineering and engineering technology students typically are afforded. The ability to apply previously-learned skills and concepts to circumstances that manufacturing engineers frequently encounter is a tremendous outcome.

It's noteworthy that this project was funded by a grant, which provided resources to allow both the OEM and SMM employees to engage with the students. Manufacturing 32 parts out of stainless steel with multiple subtractive manufacturing processes is not an inexpensive activity and is likely not repeatable every year. Still, it provided a rich learning opportunity for 8 students across two campuses and provides ongoing resources for both campuses as the parts remain at institution A and there are plans to use them for gage reproducibility and repeatability studies, GD&T studies, surface finish investigations and other relevant manufacturing operations.