# Assessing Manufacturing Knowledge Relevant to Graduating Mechanical Engineers and Addressing Shortcomings in Geometric Dimensioning and Tolerancing

A Thesis

Presented in Partial Fulfillment of the Requirements for the

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by

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# Authorization to Submit Thesis

The thesis of Jacob Gilles, submitted for the degree of Master of Science with a Major in Mechanical Engineering and titled "Assessing Manufacturing Knowledge Relevant to Graduating Mechanical Engineers and Addressing Shortcomings in Geometric Dimensioning and Tolerancing," has been reviewed in final form. Permission, as indicated by the signatures and dates below, is now granted to submit final copies to the College of Graduate Studies for approval.

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# Abstract

US industries have expressed concerns about the manufacturing knowledge possessed by recent mechanical engineering graduates. To quantify these concerns, surveys were distributed to define the areas of manufacturing education needing improvement at the University of Idaho. Specific topics were mentioned in most responses, which supported a curricular case study in this work. Geometric dimensioning and tolerancing (GD&T) was a recurring theme that could be improved upon through teaching modules implemented in existing courses. A GD&T package was created that included worksheets on coordinate dimensioning, true position dimensioning, and total indicated runout along with some visual aids. These modules prepare students on GD&T concepts through an authentic, hands-on approach that simulate on-the-job training offered in industry. Mastery of GD&T could require multiple courses which is not practical within a standard undergraduate program, but these materials provide a foundation for generating awareness on the topic and sparking interest in specialized GD&T electives.

# Acknowledgements

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# CHAPTER 1: Introduction

## Background

Manufacturing is something that has always been highly regarded in the University of Idaho Mechanical Engineering program. This can be seen in the student focused machine shop, Associated Society of Mechanical Engineers (ASME), Society of Automotive Engineers (SAE) competition teams, and capstone design projects that often include creating a functional prototype. Over the last few years, input from past graduates, industry partners, and graduate student mentors have pointed out areas of manufacturing skills and knowledge that could be improved in the recent graduates. This feedback was taken very seriously and it was decided that changes were needed to maintain the level of quality desired by the university and its customers.

## Literature Review

The topic of updating an engineering program with relation to manufacturing was initially researched to determine if other universities had come across the same challenges and if so how they went about fixing them.

In 2000, Michigan Tech went through a very similar situation. They were going through major institutional changes in the form of a quarter to semester schedule switch and it was decided they would make updates to their mechanical engineering curriculum at the same time. The focus of these changes was to introduce the students to manufacturing techniques earlier in their education and allow them more hands on lab work to get them interested. (Miller & Weinmann, 2002)

The University of North Carolina (UNC) has also gone through a similar process of trying to integrate more manufacturing education into their program. They added a new course that focused heavily on the topics of design for manufacture and manufacturing processes. The student would complete labs early in the semester that would introduce them to a manufacturing environment through the machine shop and then as the semester progressed they would use this new knowledge to implement it into their manufacturing projects. The students worked in teams to give them more group and interdisciplinary experience. To finish out the class the teams made oral presentations on their projects to help improve their communication skills on technical topics. (Ramers, 2002)

These references supported the possibility of a project to improve Idaho's Mechanical Engineering program with relation to manufacturing. Knowing other schools had gone through similar processes and been successful, it was decided to go forward with the idea. Their implementations would be used as inspiration for the work to be done by the mechanical engineering program.

Specific guidelines for manufacturing were also researched to ensure that the current student body was being taught up to date techniques, as well as verify any new knowledge aligned with these guidelines as well. ASME and the International Organization for Standardization (ISO) both produce reference data that engineers use across the world to assist in the manufacture of parts and assemblies. The standards that they have created are the baseline for the manufacturing industry to follow so companies can work together to create national or global products. Graduates of an engineer program do not need to know all of these practices, but a basic understanding would be useful in the manufacturing world.

# CHAPTER 2: Methods

## Scope of Work

The layout of this project began with multiple surveys being sent out to graduates and industry professionals. These surveys built upon each other and with the responses came data that supported the modification of the Mechanical Engineering program to better prepare graduates for manufacturing. From this data teaching materials were created to address the lack of knowledge seen with regards to geometric dimensioning and tolerancing. These materials were tested with three different courses made up of students between their sophomore and senior years. Their work and feedback was used to improve up the teaching materials with the goal of permanently implementing them into the curriculum during two manufacturing related courses.

## Initial Survey

A basis of knowledge was needed to support the idea of changing the curriculum to produce students that are better prepared for the manufacturing industry. The first step taken was to create a survey that would help identify the specific areas and topics that needed to be improved in the program. The goal was to obtain quantitative data that could be used to influence changes in the mechanical engineering program. (Spurlin, Rajala, & Lavelle, 2007)

The recipients of this survey were chosen based on their previous verbal input related to the program. Most of this input had come from past graduates of the program along with a few separate industry professionals in the surrounding geographic area. Their previous responses were the foundation of the project, so it made sense to use them as the first respondents for the survey.

The design of the survey seen in Figure 1 was to be informal and prompt the recipients to open up about their view on current engineering curriculums. Specifically, what areas of their engineering education were most important and what they believed was lacking with regards to manufacturing knowledge. They were polled on what they believed was lacking from a manufacturing perspective in the recent engineering graduates coming through their companies.

1. "If you were hiring a new engineering employee what skills and knowledge in manufacturing would you be looking for?"
2. "What additional skills do engineers need to know after the first few years in industry?"
3. "What engineering course work was most relevant to your position?"
4. "What engineering course work was least relevant to your position?"
5. "Was this the outcome you expected when you were in school?"
6. "Please share any final thoughts on the relevance of manufacturing or our undergraduate mechanical engineering program. Are we asking the right questions?"

Figure 1: Initial Survey Questions

Selection of the first surveyees was completed by Dr. Beyerlein and Dr. Odom. Both have been at the university for more than 20 years and have been involved in many of the manufacturing projects. They chose past students that had gone into the manufacturing sector and maintained strong connections with the university. This method was chosen as it would likely have a higher chance of receiving a response and the professors knew the respondents would likely have something to say.

The survey was sent out in early September and after one month the group made up of Dr. Beyerlein, Dr. Odom, and Jake Gilles had thirteen detailed responses which can be seen in Appendix A. A few areas of focus did stand out among the data which can be seen in Figure 2, but there was no clear winner from the group. This was an expected result since the population of the survey wasn’t large and the respondents came from a wide range of manufacturing focuses. An example of the feedback received can be seen in the following excerpt from an engineer in the aerospace field.

> "I would look for someone who understands the different methods for manufacturing to adapt to different production rates. For example, a car fender currently needs a very expensive die set to manufacture, but you wouldn't use that same methodology to build airplanes simply because the cost of the tools would be too great. Or, with today's 3D printing technology, some airplane parts may be able to be cost effective if printed, simply due to the cost of setup and tools versus the additive manufacturing method cost. A person who then understands how the actual design would differ is what I'd look for."

A theme noticed among the respondents was the influence of their position or field upon their responses. When someone worked in a project management position for a company that did large scale manufacturing, their mentions were topics like lean manufacturing and management experience. Those who came from smaller companies that manufactured parts in house wanted more hands-on manufacturing experience and knowledge of tolerancing.

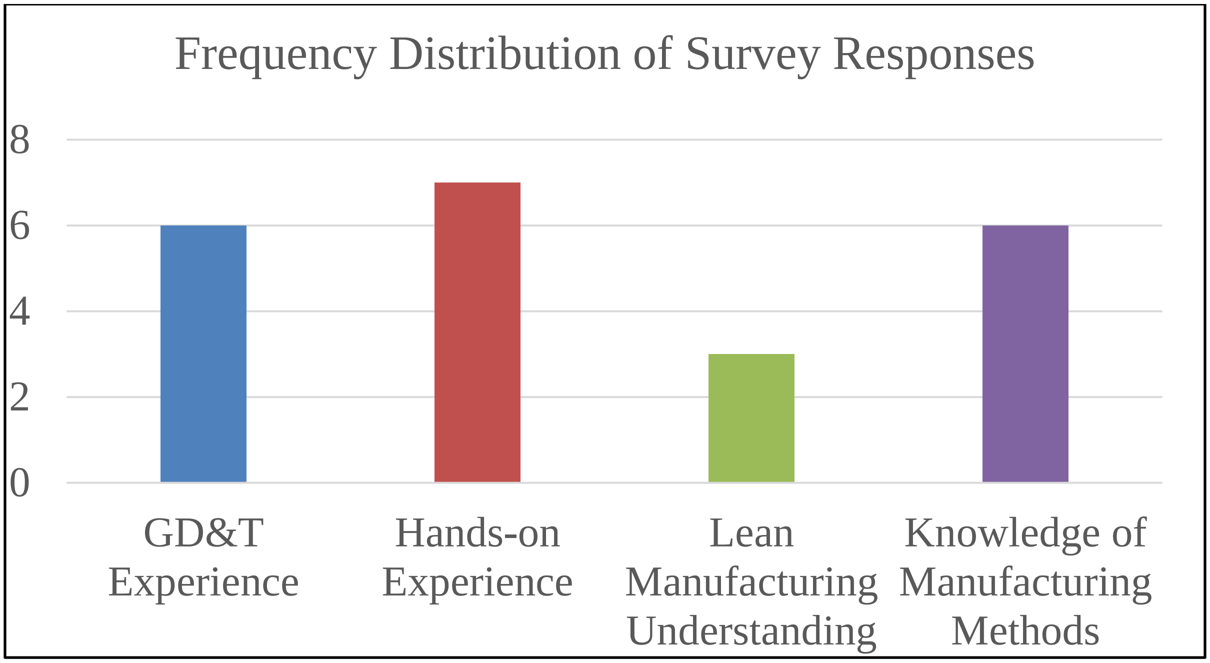



Figure 2: The four most common responses from the first survey.

These results caused the group to explore the idea of sending out a second survey with adaptations based off the first few responses to a larger group of people. It was obvious from the differences in responses that a larger sample was needed. This increase in respondents would help narrow down the possible areas of improvement for the program and show if there was a common area where students were lacking knowledge. Professors Beyerlein and Odom proceeded to meet multiple times to come up with a larger group of recipients for the expanded survey.

## International Manufacturing Trade Show

To go along with the increased amount of graduates being surveyed, it was decided that discussing this topic with engineers outside of the UI web would help reinforce the finding from the survey. The International Manufacturing Technology Show(IMTS) aligned perfectly for the group of people we were looking to survey. Attendees of the show range from small machine shop owners to large manufacturing companies with thousands of employees. Most come to see the latest tools and manufacturing processes being unveiled by the exhibitors with the goal of finding ways to improve their products. The show happened in September of 2016 and Jake Gilles attended to talk to manufacturing professionals in person about their views on what recent graduates need to know.

The conversations at IMTS were informal, but it was a very successful venue for gathering the information that was needed. Many of the professionals surveyed were very positive in giving their opinions on the subject and all were glad to know that is what something being considered at the university level. Much like the first survey there was a wide range of responses seen in Appendix B, but this time there were some common themes among them.

The following response was received from an application engineer following IMTS. The respondent works a company that make cutting tools for the machining industry.

> "[Manufacturing] Engineers should leave a BS program , particularly anyone who would be involved in machining or designing / quoting machining processes, with a solid understanding of:
>
> - Basic machining fundamentals – what is milling, turning, drilling, different forms of threading
> - Fixturing principles
> - The importance of coolant and when not to use it

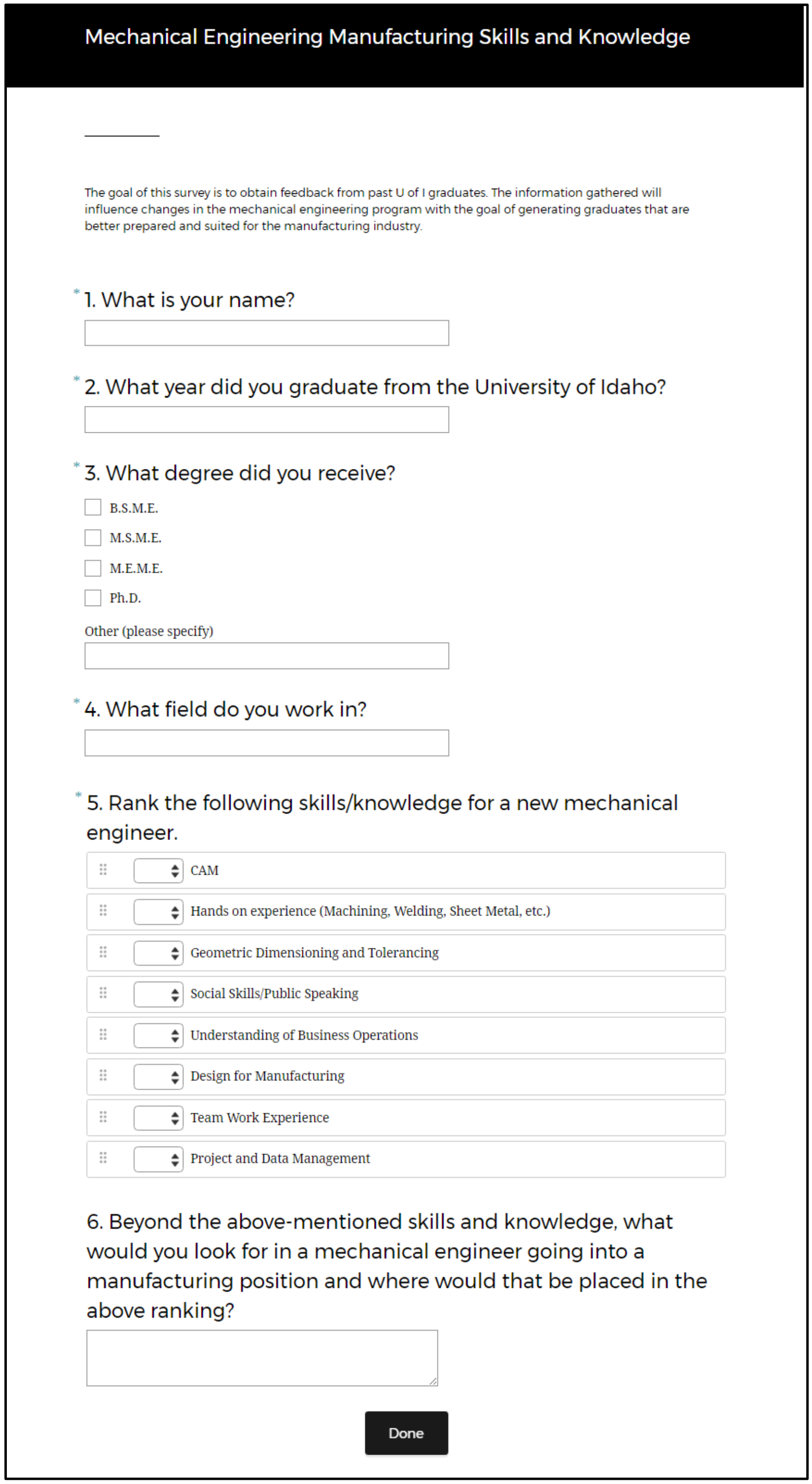
- A general understanding of materials and machining properties (especially how hardness is relative)
- What the color of chips means
- ISO material groups

There are many ways to process a product, return on investment of time vs cost is one of the most effective ways to evaluate process success. But its all relative to annual production, equipment, talent of programmers and operators."

It is easy to see from the response that the focus revolves around machining and hands-on experience that would be gained in a shop environment. This type of response showed up many times during the discussions with exhibitors at the show, which was expected. The people being surveyed worked for companies which focused heavily on a single industry which required a very similar knowledge base among the respondents.

## Newsletter Survey

To increase the number of responses and narrow down the topic of choice a second survey was created. This final survey was designed from the responses of the first survey, with small modifications that would narrow down the responses. Recipients were asked to provide some personal information that could be used to identify trends in the responses. The common topics seen in the first survey were used as the basis for question five, seen below in Figure 3. They were asked to rank the eight topics by most important for a graduating mechanical engineer. They were also given the choice to add in their own topics and give them a placement among the supplied areas based on their opinion of the topics importance.



Mechanical Engineering Manufacturing Skills and Knowledge

The goal of this survey is to obtain feedback from past U of I graduates. The information gathered will influence changes in the mechanical engineering program with the goal of generating graduates that are better prepared and suited for the manufacturing industry.

* 1. What is your name?

* 2. What year did you graduate from the University of Idaho?

* 3. What degree did you receive?

- B.S.M.E.
- M.S.M.E.
- M.E.M.E.
- Ph.D.

Other (please specify)

* 4. What field do you work in?

* 5. Rank the following skills/knowledge for a new mechanical engineer.

- CAM
- Hands on experience (Machining, Welding, Sheet Metal, etc.)
- Geometric Dimensioning and Tolerancing
- Social Skills/Public Speaking
- Understanding of Business Operations
- Design for Manufacturing
- Team Work Experience
- Project and Data Management

6. Beyond the above-mentioned skills and knowledge, what would you look for in a mechanical engineer going into a manufacturing position and where would that be placed in the above ranking?

Done

Figure 3: The second survey can be seen above as it was hosted on SurveyMonkey.com.

This second survey paralleled another survey on ABET accreditation for the university and both were sent out together as part of the fall newsletter for the college. Both surveys would reach a large number of recipients, but the expected response rate was far lower than the personalized surveys at the start of the project. Distribution of the survey was done with SurveyMonkey.com, as it was easy to create and the survey did not require a complex format.

While this survey was being sent out to graduates, it was also administered to a group of industry professionals at a Society of Manufacturing Engineers (SME) meeting in Seattle, WA. The meeting was mainly focused around the current ordeals of the inland Pacific Northwest SME group, but attendees were very interested in the survey and the possible impact of it on current engineering students. Eleven responses were obtained at the meeting that would be paired with the online survey.

The responses for this survey trickled in over a period of three months, with a total of forty graduates submitting responses. The top three ranked skills were recorded from each respondent and then sorted to see which the most recurring themes were. These outcomes can be seen below in figure 4 and the supporting data can be seen in Appendix C. Team work was the skill mentioned most with over half of the respondents having it in their top three. Project management and design for manufacturing (DFM) experience followed with both showing up in just over half of the responses.

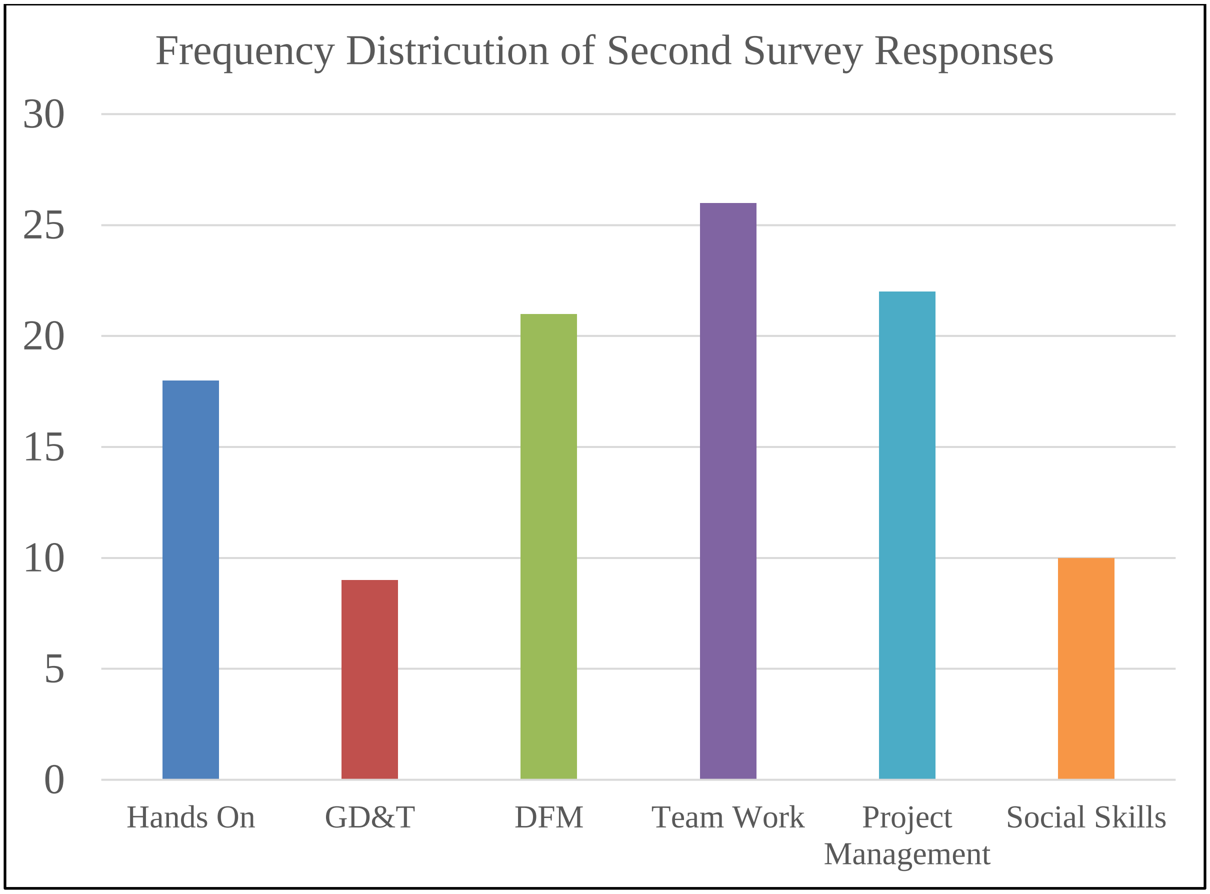



Figure 4: Six most noted topics from the second survey.

One major drawback that can be seen in the data above is the dominance of the overarching principles that were included in the rankings. Topics like team work experience, social skills, and project management were some of the highest-ranking topics, but these are already major areas of focus for the program. It was decided that these ideas would not be directly addressed in this project, but they would be considered when the teaching materials were being created. Design for manufacturing and GD&T are topics which have normally been learned by students in the machine shop, but they have not been formally taught the subjects in recent years.

From this survey process one graduate did directly reach out to Dr. Beyerlein with a more detailed response than he was able to supply in the online ABET survey. He is a project engineer in the material handling sector and he included the following in an email to Dr. Beyerlein that covered his concerns on the topic.

> "Another big problem that I see with new engineers (and old stubborn ones) is drawings and tolerances. Errors with drawings add risk because intent can be lost and manufacturing ends up costing much more. We also see a lot of miscalculation with tolerances which can significantly increase cost and often after review when trying to reduce manufacturing cost find if wasn't necessary."

This type of highly detailed response is a great example of what the group was looking for. It focused on an area of knowledge that students are lacking and provides an example of how it was impacting the company.

## Selection of Focus – GD&T

With the data from the surveys collected, a decision had to be made on which topic to pursue. The three areas mentioned most were hands on experience in a manufacturing environment, geometric dimensioning and tolerancing, and design for manufacturing. All of these topics are important for a mechanical engineer to know, but it would have to be decided which could be accomplished in the desired time frame and still have a measurable positive impact on the curriculum. After detailed discussion, it was decided that the topic of GD&T made the most sense. It was something that the group had experience working with through projects in the machine shop, but the current student body had no formal teaching on the topic. This combined with the recurring mention of it in the survey responses made it a viable route to pursue. The other two focuses would also be included in the work wherever possible to help address the shortcoming of their teaching.

Another influencing factor to the decision was the ME404 Design Intent class being offered in the spring semester of 2017 focused around the reverse engineering of parts and assemblies. This class could serve as the first test bed for new teaching materials. The class was made up of a small selection of students with above average exposure to design work and a majority of the students had already taken the summer lean manufacturing course. This meant they already had some hands-on manufacturing work and basic tolerance knowledge. On top of this class, there were small changes being planned for the programs Solidworks course, which would allow for integration with teaching materials created from this project. Both of these classes would make up a strong testing platform that would show the impact of this project and prove out the material for use in the upcoming lean manufacturing course of summer 2017, where the majority of changes would be implemented.

One aspect of the teaching modules changes that the college wanted to address was the typical dryness of work done on GD&T. The drawback with standards like ASME Y14.5 is that even though they do cover all of the necessary GD&T information that an engineer could need, it is written for someone who already has the basic knowledge at hand to use it. People who have no experience with GD&T or tolerancing of any kind will find reading through it daunting and difficult to understand. Trying to use this type of standard as a reading assignment could start students off on the wrong foot with regards to GD&T. (American Society of Mechanical Engineers, 1966)

The first idea was to use some sort of hands-on example to supplement reading that could attempt to counteract this blandness. The idea would involve creating sample parts that could demonstrate exaggerated examples of the teaching topics so students could see and feel what was being discussed. This sounded great as an idea, but a large amount of work would be required to implement it successfully. Designing and manufacturing the tools would take some time, but the most daunting part would be creating them in a way that a majority of the students would be able to understand the material being shown by the interactive hardware.

The second idea that came up during a thesis meeting was to just drop the students into the deep end. This would work by giving them a very brief introduction to some of the main topics of GD&T followed by a worksheet that would focus on basic problems involving these topics. A class would be divided up into groups of two or three to work through the problems. The main goal would not be to have the students successfully complete the whole worksheet, but use it a catalyst to get them thinking in depth about the GD&T topics. They would be able to discuss their answers between groups and attempt to figure out inconsistencies among themselves before coming to the teacher. A requirement of this idea was that the students would need to have some experience with a simple dimensioning scheme, so the introduction did not have to be overly long or detailed. The group believed the students would be prepared for this through the ME301 Solidworks class. This course exposes the students to a wide range of drawings packages, with some ranging up to 100 years old being used for the final projects.

Based on this experience it was decided that the worksheet idea could work out if it was laid out correctly and had supporting tools to go along with it. The material would have to be organized in a way that would lead the students through the topics in an ascending order of difficulty and slowly work them up to more complex problems. This would include breaking up the topics of GD&T into multiple worksheets based on difficulty and length. The first being focused around the ideas of general dimension schemes and tolerance stacking, while the final worksheet would likely cover true position dimensioning schemes and more complex fitments of assemblies. It was noted that these materials would not focus on making the students experts, but focus more on showing them how complex tolerancing can get and why they should begin to think about it when designing their own products.

To quickly ensure the students going through this exercise were prepared to answer the questions, a very quick and concise introduction would be formed. This would be explained by the instructor prior to starting the exercise and could be paired with some basic hands-on examples that help explain the upcoming topics.

# CHAPTER 3: Coordinate Dimensioning and Tolerance Basics

## Coordinate Dimensioning Worksheet Design

To accurately cover a majority of common dimensioning techniques it was chosen to cover both coordinate and true position styles. Coordinate dimensioning using two lines referenced from two different planes to define the location of a feature, then tolerances are added the linear distances to create a rectangular acceptance area for the feature. True position schemes use the same set of lines to define the ideal location of a feature, then incorporate a circular area centered at that point to create the acceptance area. True position schemes show their benefits when assemblies become more complicated and require fitment between large ranges of parts produced at different times or locations. To transition students into learning these techniques coordinate dimensioning would be used first as it is generally easier to visualize without previous shop experience.

The first step to implementing these GD&T teaching modules was to create an initial test worksheet that would cover general tolerancing principles. This would gauge how much the current students already knew on the topic without formal introductions or teachings. The answers would act as a baseline for the group to be able to design the following teaching modules around. Areas that a majority of the students had difficulty in would be addressed by including more questions on the topic and a hands-on example that could support the idea. After completing the testing, the first worksheet would be adjusted to better fit the needs of the students based on their first answers. This would allow a range of different tolerancing principles to be covered, while adapting the information to the skill level of the students.

Deciding on a timeframe for the worksheet was difficult, as it was expected that every group of students would work through it at a different rate. The original goal was for the assignment to take around 45 minutes to one hour to finish. This would give them the most possible time to work through it, while maintaining enough time to check answers and address questions from the students.

The coordinate dimensioning worksheet in Appendix D would be paired with a drawing set for the Block Project (Figure 5) in Appendix E. Students would reference these drawings as a basis for the worksheet questions. This specific assembly was chosen as it had been produced hundreds of times at U of I and there were many examples of hardware which could be passed out to students while they worked through the assignment. Ideally this would help them easily understand the features being shown in the drawing package. (Allen, 2002)

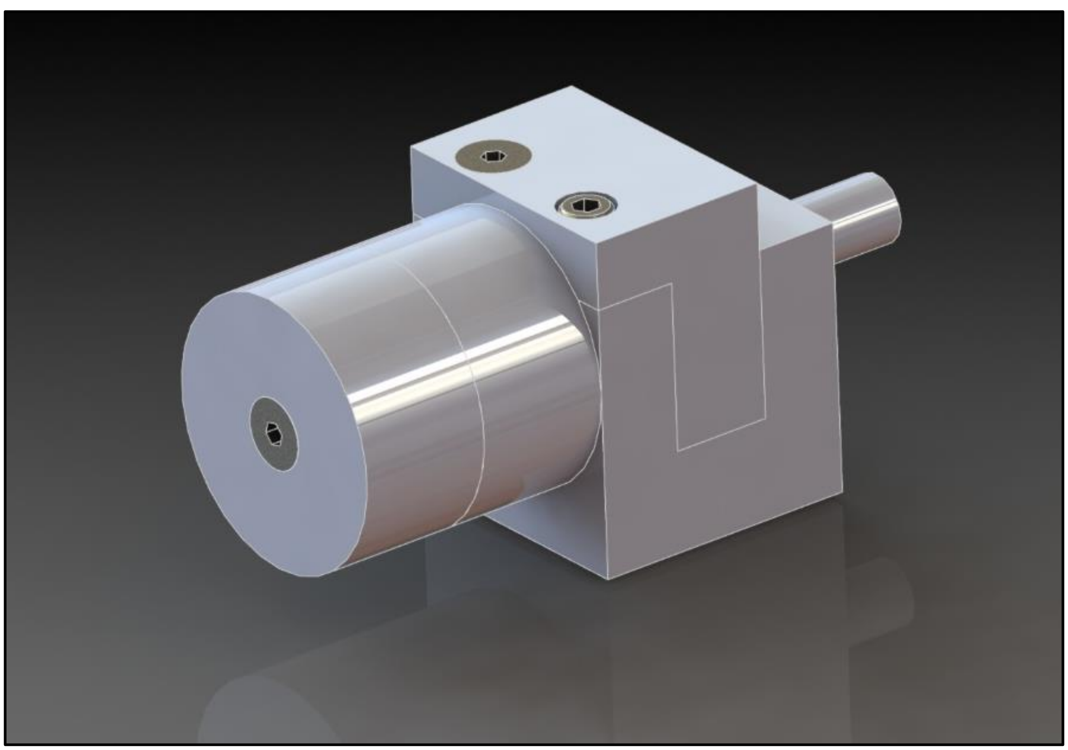


Figure 5: A render of the assembled block project.

To begin the assignment, it starts off with a few basic questions that focus on reading tolerances and the stacking errors that can arise when using a coordinate dimensioning scheme. Problem 1 seen below in Figure 6 requires the students to reference part 2-01 in the Block Project Drawing package in Appendix D and then calculate the maximum and minimum values for a toleranced dimension. To complete this question the title block must be referenced to obtain the default dimensions. This starts the users at one of the most basic steps for drawings and dimensions, but it also ensures that they have this knowledge before moving on to more difficult topics.

Coordinate Dimensioning Block Project Worksheet

(Assume Non-Specified Dimensions Are Nominal)

1. What is the maximum possible center to center distance between the holes using dimensions 7.A and 7.B?

Figure 6: First problem the students encounter on the worksheet.

The next two questions seen in Figure 7 revolve around the grooves on part 1-04 in Appendix D. Problem 2 adds another level of difficulty compared to the first as it includes two dimensions with tolerances that require the user to take into account the sign of each value. These signs must be noted, since the measurements are working in opposite directions off parallel planes. This aligns with the first rule of the Plus or Minus handbook, which states "The tolerance on any length is equivalent to the sum of the tolerances on the dimensions, added or subtracted to achieve the length". The third problem also introduces is the idea of the typical callout that allows the author to reduce clutter on a drawing by dimensioning similar features with one dimension, instead of each instance separate. (Dobie, 1942)

2. What are the maximum and minimum distances between datum A and edge 5.B?

3. Is the diameter dimension for all of the grooves on part 1-04 the same? Explain.

Figure 7: Problems 2 and 3 focus on the lathe pin and its grooves.

Problems four and five both seen in Figure 8 relate to the ideas setting tolerances so that the reference surfaces for parts 2-01 and 2-02 are always the first to contact each other. The questions ask students to calculate which surfaces will contact first when the parts are assembled, based off the given dimensions. This was done to address a common issue seen in drawings created by students for use in the machine shop. Students would often dimension critical features using edges or datums that had no real importance to the parts. This often caused major stack up issues when trying to manufacture and assemble the pieces. These questions also reinforce the detail that is required when correctly assigning dimensions to parts, especially in mating assemblies where errors can propagate.

4. Which edges are most likely to contact first when part 1-01 and part 1-02 are mated. (Assume they are perfectly concentric. Use dimensions 3A, 3B, 4A, and 4B.)

5. Is it possible for edge 8.C to contact the bottom block prior to edge 8.D when the parts are assembled correctly and everything is in tolerance?

Figure 8: Questions relating to the assembly of the Block Project.

Next up is another problem that consider the ideas of over dimensioning a drawing. The students are asked to calculate the range of distances a hole on part 2-01 in Appendix E can lie from a mating edge as seen below in Figure 9. Due to the way the drawing was originally dimensioned, there are two possible outcomes for this answer, due to over dimensioning on the print. The goal here is for some of the students to get one answer, while the rest have another. This will hopefully cause them to investigate the issue after being prompted to look for issues. The goal is for them to discover the two possibilities and see how easy it can be to over tolerance a drawing.

6. What are the maximum and minimum distances that edge 7.E can lie from datum A on page 7? Are there any issues with how this edge is dimensioned?

Figure 9: Prompting the students to search for issues in the drawing package was done to show them the difficulty in finding errors.

To reinforce the ideas being covered in the previous questions, there are multiple questions asked throughout the assignment (Appendix D) looking for explanations to the common issues students are continually seeing with the given drawing package. The goal is to cause them to look deeper into the drawing package and start picking it apart for issues. The act of them doing this will likely cause them to look for these issues later in their own drawing packages.

The final technical question for this assignment can be seen in Figure 10. It involves working through a multitude of dimensions to figure out if part 1-04 will fit through both blocks at a given set of analyzed dimensions. This question involves many steps and can become complex due to the large amount tolerance stacks that must be kept track of. If the students complete the problem correctly they will find that will all of the supplied dimensions the pin will not fit through, even though all of these dimensions are considered in tolerance. The goal here is to show them the complexity that is required to correctly define a mating part system using a coordinate dimensioning scheme, especially when the mating parts are round.

9. Imagine an instance of this assembly where the true manufactured dimensions are given below. Assuming all other dimensions are at their stated ideal dimension, will the lathe pin fit through the blocks? If not why and what could be done to alleviate the problem?

| | Description | Measurement |
|---|---|---|
| 5.A | Lathe Pin Diameter | 0.5020” |
| 7.C | Pin Hole Location | 0.6260” |
| 8.A | Pin Hole Location | 0.6250” |
| 8.B | Shoulder Height | 1.2470” |
| 8.F, 7.H | Reamed Hole Diameter | .5050” |

Figure 10: The final question of the coordinate dimensioning worksheet.

With the worksheet finished, the instructor for the session will proceed to go over the assignment in detail. Students will be asked to give their answers to problems, as well as explain the process they used. This will allow the instructor to make sure students have the correct answer and understand the approach so they can use it on future work. Those who finished the assignment can help by explaining their methods to students who did not get as far. By doing this the students with correct answers can reinforce their good habits, while teaching others.

Common mistakes to look for when using the worksheet are misreading the default dimensions in the title block and forgetting negatives when dimensions are used in opposite directions on the same axis. Both issues will cause errors in calculations which can be easily seen when reviewing the work. The instructor could also remind students to use extra caution when dealing with these aspects of the drawings.

## Initial Testing – ME404 Design Intent

To begin testing the worksheet, the Design Intent class being taught by Dr. Odom was used as the first test bed for the material. The ME404 Design Intent class was built around the ideas involved in reverse engineering parts and trying to figure out what the designers were thinking at the time of design. Specifically focusing on projects or parts that are not currently being manufactured and drawings are unavailable. For example, when a hydroelectric generator is overhauled how can the contractor doing the work figure out the dimensions and tolerances of parts when there are no drawings. The original builders are commonly out of business and the parts are worn heavily due to long term use. The students enrolled in this class would be an example of ones who had the most experience with GD&T through their education, so they would likely be most qualified to complete the initial assignment in its original form.

A 45 minute meeting period of the class was used to administrate the worksheet and the students were allowed to work together on the assignment. This was done, because the faculty believed the discussion created by the assignment would cause the students to go back and forth between each other on the topics. This would also force them to explore more possibilities and concepts that they find in the drawing set. Additionally the groups would hopefully be able to find their own issues and fix them prior to turning the assignment in.

At the beginning of the worksheet, it was explained that their answers would be used as a basis for the difficulty and length of the assignment. They were told not to rush, but thoroughly think through the problems and discuss it with others if needed. It was also explained that the worksheet was going to be a tool to introduce the concepts of tolerancing to students. They would not be experts after the assignment, but it would act as a basis for them to research it more on their own and have a respect for the subject.

The activity was observed by both Dr. Beyerlein, Dr. Odom, Jake Gilles, and Bill Magnie the shop supervisor. Their goal was to watch and record the problems that students ran into on the assignment. Some of the issues could be ones that the faculty want the students to work through, while others could occur from a lack of clarity within the assignment and therefore be updated to make the assignment better. The worksheet was collected to check the student's answers as well as record their comments on the assignment. Explanation questions were built into the sheet to spark their minds on what could be changed in the drawing to improve it and what recurring issues they saw from the given dimensioning scheme.

Reception overall was very positive from the class and they had useful feedback for changes that could be made to the assignment. Multiple problems needed wording changed to help the students correctly understand what was being asked. Some students mentioned that and introduction covering the basics of tolerance stacking, datums, and mating parts could be helpful prior to working through the assignment. This supports what was discussed early on in the meeting, but wasn't designed yet. All of these concerns would be addressed through updates to the worksheet and the addition of material for the instructor.

Something that was mentioned by multiple students was the possibility of adding a section that explained some of the design considerations that should be taken into account with regards to tolerancing and manufacturing. This lines up with well with topic of design from manufacturing that was mentioned in the surveys by a majority of the respondents. It is something that could be mentioned during the worksheets and teaching modules of this project, but it would likely require more time than currently available to properly teaching some of these techniques. The students were encouraged to take the summer Lean Manufacturing course if this is something they were seriously interested in, as many of the basics for DFM can be learned in the course.

As for time frame, the assignment was not completed by most of the students. Only two of the 5 groups reached the last problem and the remaining students were at different points in the assignment. There was also a noticeable amount of time spent explaining what the questions were asking for, as well as time spent receiving the student's feedback. Considering this it was decided that the length of the assignment would not be changed at this point. After the noted changes were made it would be tested again with another group of students to validate the updates and narrow down the required time.

## Final Testing - ME301 Solidworks

With the changes made the next step was to test the improved worksheet with a larger group of students at a different point in the curriculum. The ME301 Solidworks course was chosen as the students were commonly either sophomores or juniors and the class size was almost sixty in three different sections. This would give another strong reference point for the current work being developed and impact what else could be added into the program to prepare students at this level. Another point that had to be taken into account was finding a time when the worksheet could be administered, without negatively impacting the course. The class has an assignment related to measuring physical parts about two months in that lined up well with the GD&T teaching module. It was also a time that had often gone unused in the class, so this assignment would be able to be administered without holding the students up on the rest of their work.

A big question that this iteration would hopefully address is the different knowledge level of this student group versus the first that worked through the assignment. The group was unsure if the content would be too difficult for some to work through or if it would be doable by these students earlier in their education.

One idea that did come up was if these students would need some sort of introduction to the topic before being able to finish this assignment. After discussing the outcome of the ME404 test is was decided that the students could likely work through it with their current knowledge from the ME301 Solidworks course and earlier design courses ME223. An idea mentioned earlier on was chosen, which would create a note sheet for the administrator of the assignment which could cover the topics that came up in this iteration. Then in future classes when this worksheet is given out the teacher or graduate student leading the class could have answers for the common questions that come from the students. This would also align with the idea of letting the students learn by doing, but being prepared for the common difficulties that come up.

Most of the issues noticed in the first round of testing came from incorrect calculations when figuring out tolerancing stacks and misunderstanding on the default tolerances on the supplied drawing set. To overcome the first issue the student groups would be prompted to check their answers with the other groups with the goal that they would be able to catch their mistakes that way. The second issue of not knowing how to properly read default dimensions would be covered by explaining the ideas covered before starting the assignment. This topic is covered in the Solidworks class when starting drawings, but it was obvious that the students hadn't worked tolerances enough at this point in the class to recall the process.

The outcome of the ME301 test also showed that the time frame required for students to finish the worksheet varied wildly. During a seventy five minute period a two person group was able to finish in forty minutes and then began asking questions related to true positioning, while other groups of two and three barely made it through half of the assignment using the whole period. This wide range of completion times was expected as it was often seen in other subjects or classes by professors. It was decided that the length was acceptable for now and could be changed later after more students were able to work through the material.

During this testing the instructor would go over the assignment with students as they finished, but this was done separately with each group. Ideally the whole class would be able to go over the assignment together before the class ended so that the correct answers could be explained. This was reinforced after the test when the assignments were analyzed. Many of the questions had incorrect answers with explanations defending them that were based upon incorrect concepts. This type of result needed to be thinned out if not eliminated. It is especially important at this level for the students to have a strong understanding as they will build their GD&T knowledge upon these topics.

To combat these incorrect answers at the end of the class, the assignment would be ended fifteen minutes before the period ended to give a time for the instructor to go over the answers and address questions from the students. This step is critical, because if the students are allowed to leave the assignment thinking they have the correct answers it could cause issues with them building their future knowledge on an incorrect foundation. Just as with math, most of GD&T is built upon the previous topics, so it is critical to ensure a strong understanding early on.

# CHAPTER 4: Geometric Dimensioning and Tolerancing

## Hands-On Teaching Tools

For students earlier on in their education it may be chosen to stop here due to time requirements in the curriculum. For students at the senior level or those currently enrolled in the lean manufacturing class this is an ideal point to transition them to begin learning about a true positioning dimensioning scheme. At this point they should have a basic understanding of tolerances and they are more likely to have worked on projects in the machine shop.

To accomplish this smooth transition, the second worksheet would be paired with block project as well. The major difference would be in the addition of symbolic callouts in this version of the drawing package visible in Appendix F. This would allow the students to apply these new concepts to the same project and see the differences. Plus, for the students taking Lean Manufacturing they would immediately follow this by building the project, allowing them to test out their new knowledge on machine parts. Hands-on experience with measurements and GD&T like this is something that came up frequently in the survey responses and this was seen as an effective way to address the issue.

This final worksheet would be covering topics that most students would have never seen before, so a more in depth introduction would be required. Ideas like maximum material condition, basic dimensions, and positional tolerances are all crucial to learning a true position dimensioning scheme. Following the same of idea of keeping the content interesting and interactive it was decided that a combination of a teacher explained handout and hands on examples would be used to convey the ideas being covered. This would allow the students to learn about a concept and then immediately be able to see the implications of that concept in front of them on manufactured parts.

Accomplishing this would entail designing and creating assemblies or parts that could easily convey the concepts being taught. The starting point for these designs would be examples from some older teaching materials that the group had access to. The most impactful of these is the Boeing Industrial Relations Training book on Geometric & Positional Dimensioning & Tolerancing.  This manual was used as the basis for teaching GD&T at the Boeing Company beginning in the 1960's and contains many great examples that explain the different concepts of a true position dimensioning scheme. Most of these examples have very detailed diagrams which work to show the benefits and uses of the topics covered. An example of these diagrams can be seen in Figure 11 where the manual is showing the benefits of a true position dimensioning scheme. (Boeing Company, The, 1965)

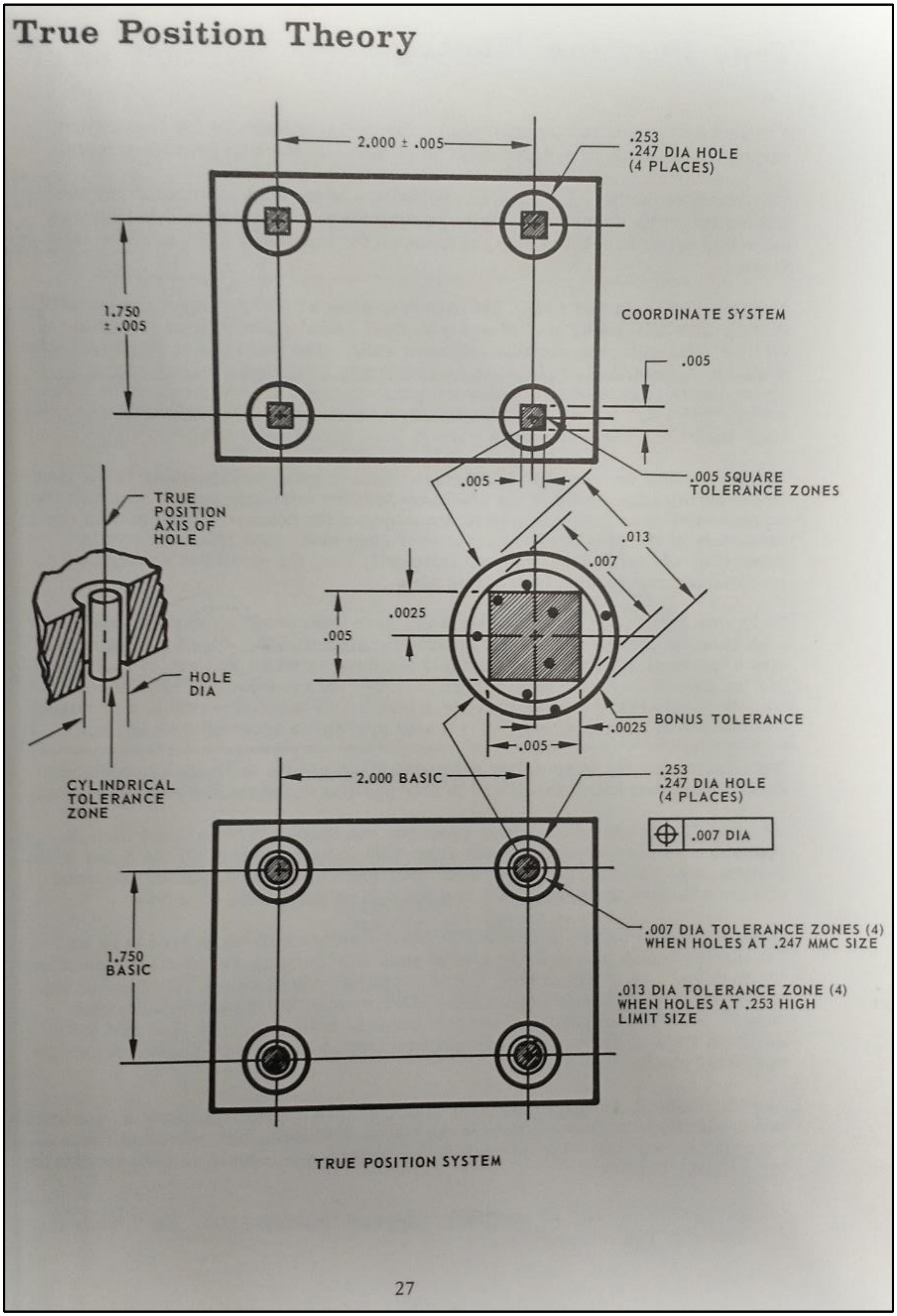



Figure 11: An example of the illustrations from the Boeing GD&T Manual.

Two issues arose in the transition of the examples from paper to metal and wood. First being the book uses typical values for machined parts in the range of thousandths of an inch. While these values are common in the world of machined parts, it can be difficult to spot small changes with the naked eye on a machined part. The second issue is that most of the examples use tools like section views to show what is happening in detail. This can be very helpful on paper, but very difficult to apply to manufactured parts. Both of these issues would have to be addressed so the tool would be successful at teaching students these new concepts.

To address the first problem the hands-on examples would show enlarged views of the tolerance areas, similar to the examples seen in Figure 11. The Boeing manual was used as inspiration for the parts, but some dimensions were changed or exaggerated on the machined example parts. This would allow students to easily see the differences between different dimensioning schemes.

The second issue was far more difficult to solve. Conveying what is going on inside a part or at point that does not actually exist in the real world can be incredibly difficult. The first idea for a tool that would assist with explaining the concepts of a true position dimensioning scheme versus a coordinate dimensioning scheme was a part made from layered wood pieces. It contained dimensions and explanations laser engraved into the wood as seen in Figure 12. Along with this part the drawing seen in Appendix G would be supplied to show students how each of these styles would be called out.

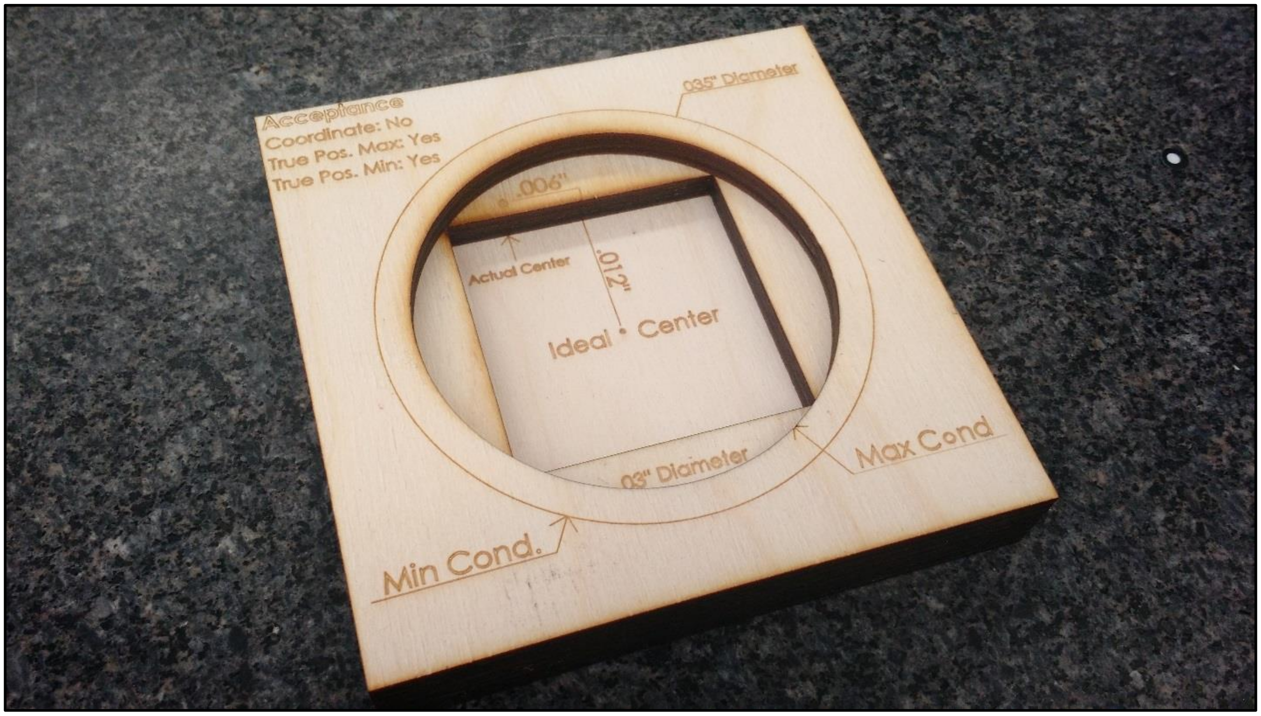



Figure 12: The final wooden true position tool with the layers visible.

The idea behind this tool was it would show the "free" increase in area that can be gained by dimensioning round mating parts using true position. The base layer contained an "zoomed in" view of the allowable area that the hole center could lie in and be accepted in a quality control process. The second layer glued on top of the first had the circular location defined by a diametric true position tolerance that intersected the first layers square at the corners. The circular segments seen on this layer represent allowable center locations at maximum material condition and represent an increase of more than 50% for the allowable acceptance area. The top layer of this tool consisted of showing the final acceptance area increase through having either the pin or the hole move away from maximum material condition (MMC) to least material condition.

This tool was tested with a small group of students while explaining the ideas of true position and its reception was mixed. Some students were able to see the ideas being presented, while others had trouble. The most notable issue with the tool was the fact that is was completely static. Layers of the part were not able to be moved, therefore students were forced to imagine the circular pieces being represented. Ideally the layer would be able to have lines engraved on them representing the mating pieces. Then if the layers were free to move students could adjust the pieces to visualize configuration in which the parts may or may not fit together. Major problems with this idea were that when the pieces were free to move they would cover up the engravings on lower layers. There was also the issue of not being able to show the center locations of the circle, as the areas where they would be was removed in the laser process.

The solution to this problem came abruptly after seeing a student project made out acrylic. Using acrylic as the material would allow the same features and dimensions to be etched onto the material without worry of blocking the lower pieces. It would also allow the centers of the circles being represented to be placed onto the layers so the true center of the circle could be seen during movement.

One issue that arose with the first acrylic prototype was the difficulty of seeing the etched areas. If the pieces were placed on a surface with a light or neutral color it became difficult to make out the etching. The first idea to combat this issue was the addition of color to the etchings. Paint pens were used to accurately add colors to the etchings which allowed them to stand out on a much wider range of surfaces. This also allowed the use of different colors which would be used to identify each line instead of adding more etchings on the surface to explain what each line is. The tool with improvements can be seen in Figure 13.

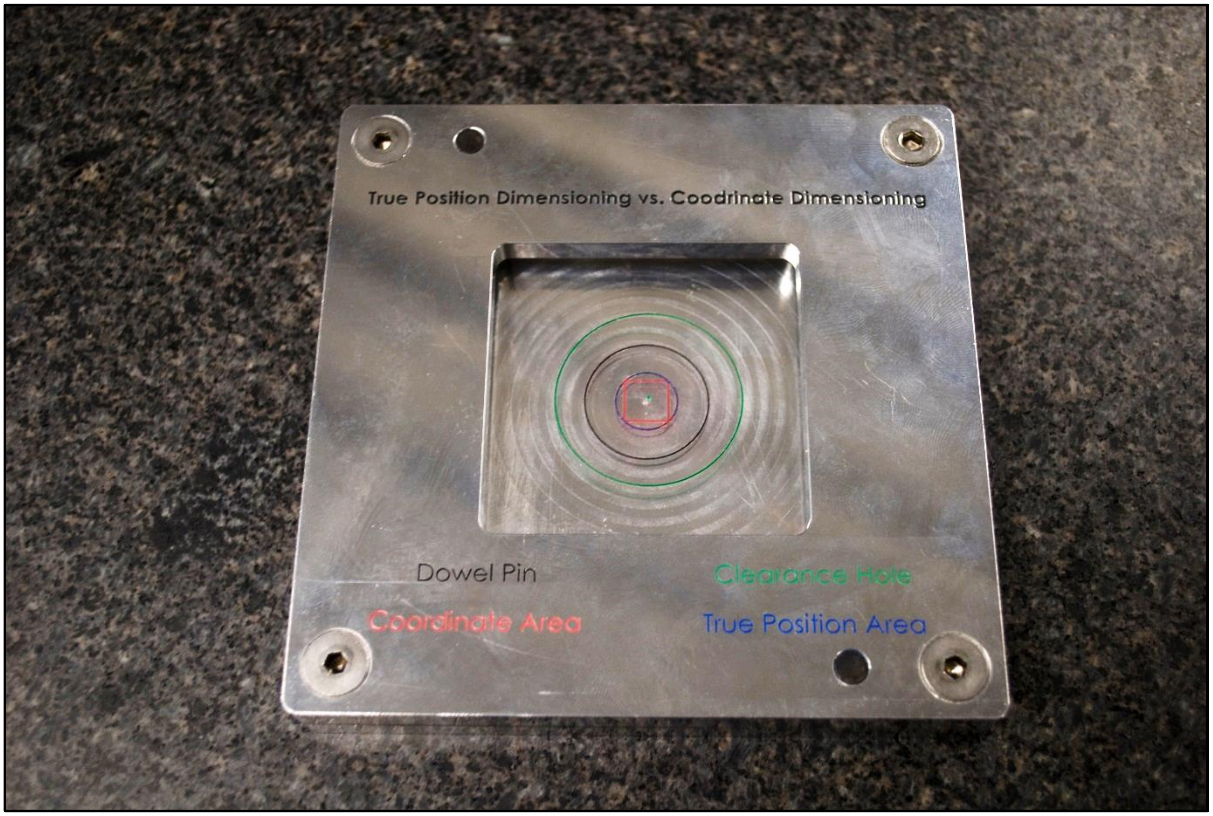



Figure 13: The first true position tool to use acrylic sheets and an aluminum housing.

Along with the addition of colors to the acrylic pieces, it was decided that a metal housing for the parts could be beneficial. This would contain the pieces so they remained in the correct orientation and the extra surface area could be used for references or instructions. Additionally, with the housing made out of aluminum it could be anodized to make the colored lines on the acrylic stand out as much as possible.

## True Position and Symbolic Dimensioning Worksheet

Addressing the lack of knowledge with regards to symbolic dimensions was done with a simple handout (Appendix H) covering the most common symbols and callouts. The handout shown in Figure 14 would be stepped through at the beginning of class by the teacher and questions could be asked to clarify the ideas before starting the assignment.

There are many more symbols and concepts that could be covered by a worksheet focusing on symbolic dimensioning, but it was chosen to just include those which were required for the upcoming worksheet. (Henzold, 2006)

## True Position Basics

- Basic Dimension
  - Contains no tolerances
  - Specifies ideal location
  - Called out with the number boxed
    - |← [20.2] →|
- Maximum Material Condition
  - The dimension at the edge of the tolerance range which leaves the part with the most material or volume.
  - Holes at their smallest allowable diameter or pins at their largest diameter
  - Called out with MMC or (M)
- Datum
  - References edge for dimensions
  - Called out with boxed letter linked to edge [A]
  - Best placed on mating surfaces
- True Position
  - Acceptable area for location of parts
  - Typically used for round features that mate with other parts
  - Called out with bulls eye ⌖ and diameter ∅ symbols
  - Commonly uses MMC
  - Must reference at least one datum
  - Acceptable area is increased if the feature is between MMC and LMC
  - Example: | ⌖ | ∅ 0.030 | A | B |
- Mating Parts
  - Fixed Fasteners
    - Dowel Pins, Threaded Holes, Etc.
    - Diameter Positional Tolerance = (MMC Hole – MMC Pin)/2
  - Floating Fasteners
    - Bolts and nuts
    - Diameter Positional Tolerance = (MMC Hole – MMC Pin)
- Total Indicated Runout
  - The greatest range of movement recorded with a dial indicator along a feature when it is rotated about the datum or reference line.
  - Commonly abbreviated TIR
  - Called out with two connected arrows ⌰
  - Must reference a rotational datum surface
  - Example: | ⌰ | 0.030 | A |

Figure 14: The true position basics handout is a reference tool for the worksheets.

To begin the true position worksheet in Appendix I, the first four questions seen below in Figure 15 focus around trying to convey the idea of maximum and least material conditions. Students are asked to find the maximum and minimum diameters for a hole, then immediately give the maximum and least material condition for the same hole. The goal here is to try and convey the transition from largest and smallest to MMC and LMC. Ideally this would give them enough understanding to apply it reading a true position callout. Additionally the fourth question asks for the maximum material condition of a pin, which would be the largest diameter. Understanding that the MMC of a pin and hole are opposite will be necessary later in the assignment.

Name: _______________, Name: _______________, Name: _______________
Number: ______ Number: _____, Number: _____

True Position Block Project Worksheet

The next few questions focus on correctly specifying the location of the holes (7.A and 8.A) that the pin fits through.

1. What is the smallest diameter that hole 7.A can be while remaining in tolerance?

   ______________________________________________________________

2. What is the largest diameter that hole 7.A can be while remaining in tolerance?

   ______________________________________________________________

3. What is the maximum material condition for hole 7.A? ________________
   Least material condition? __________________

4. What is the maximum material condition for the lathe pin diameter? ______________

Figure 15: The first four questions of the symbolic dimensioning worksheet.

Following these basic questions, the students are asked to identify all the symbols used in a true position callout for problem 5 shown in Figure 16. The goal of this question is to have students focus on the callout enough that they can easily remember the ordering on the symbols and what is required to specify the location of a feature. The example shown in Figure 16 is meant to be similar to all of the true position callouts used in the Block Project drawing package. (Appendix F)

5. Label each of the symbols shown in the true position callout show below.

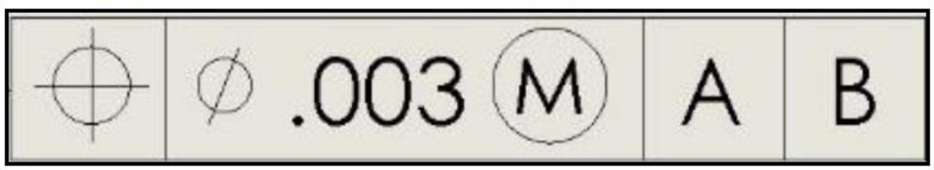
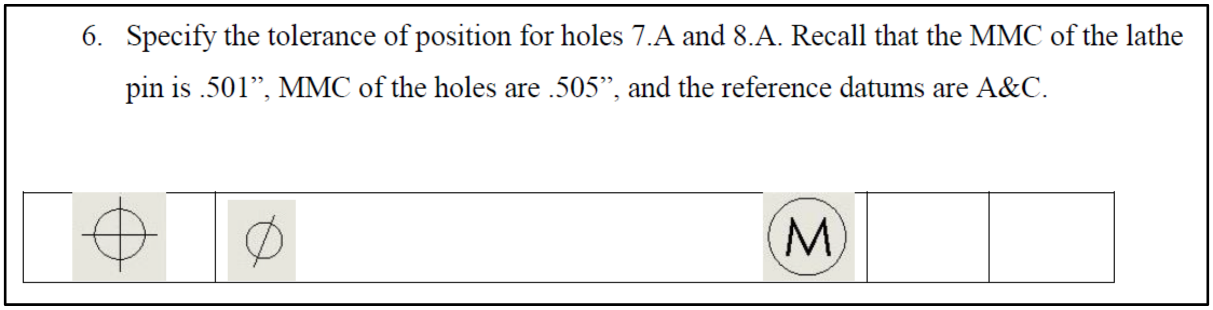



Figure 16: Students must identify the components of a true position callout in problem 5.

Once the students have an understanding of how the callouts are laid out, they are asked to specify a positional tolerance for two holes in the bottom block sub-assembly. In Figure 17, problem 6 is shown supplying the students with the required limits of the holes and pin, along with the datums to reference the dimensions to. One topic that students should be reminded of for this problem is the idea of fixed fasteners vs floating fasteners. This information can be found in the reference sheet and it contains the equations required to calculate the correct tolerance.


6. Specify the tolerance of position for holes 7.A and 8.A. Recall that the MMC of the lathe pin is .501", MMC of the holes are .505", and the reference datums are A&C.

| ⌖ | ⌀ Ⓜ | | |
|---|---|---|---|

Figure 17: Question 6 implements the newly learned symbolic dimensioning method.

As a reinforcement for the calculations used in mating part schemes, the following question 7 in Figure 18 asks if a given true position callout would work for the referenced features on the blocks. This requires them to reference dimensions in the drawing package then work backwards from the callout to ensure the callout is correct. As with problem 4 the required equation is supplied on the handout. The problem then asks for their reasoning which can later be checked to ensure sure they used the correct method to reach their answer.

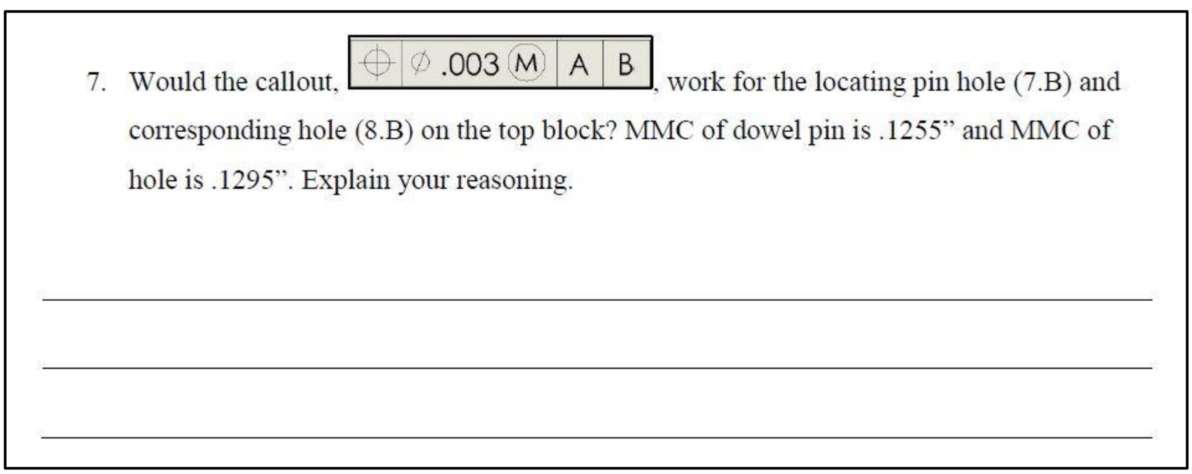

7. Would the callout, ⌖ ⌀ .003 Ⓜ | A | B, work for the locating pin hole (7.B) and corresponding hole (8.B) on the top block? MMC of dowel pin is .1255" and MMC of hole is .1295". Explain your reasoning.

Figure 18: Problem 7 focuses on the locating holes on the bottom and top block.

Next up the in problem 8 the students are supplied with three dimensions and asked if the associated part would be accepted based on the drawing package. The supplied dimensions in seen in Figure 19 are used to represent measurements taken from a coordinate-measuring machine or optical comparator. This aligns with how a manufacturing company would check the dimensions of a part like this to ensure it satisfies the give true position dimensions. The calculations and decision for this problem require a solid understanding of the geometry behind true positioning. If students are able to correctly answer the problem, it shows they have the basic ideas of true position down.

8. Given the following measured dimensions for hole 7.B, would the bottom block be accepted or rejected using the tolerance on the drawing? Explain your reasoning.

| Center distance to edge A | Center distance to edge B | Diameter of Hole |
|---|---|---|
| .9990" | .3135" | .1250" |

Figure 19: Problem 8 simulates a quality control check based on industry techniques.

With these questions answered the worksheet moves on to ask students a final question regarding the benefits of true position. They are asked to explain the benefits they see with this type of dimensioning scheme versus a strictly coordinate dimensioning scheme. Ideally this question should be very easy after working the previous problems, since they focus on teaching true position while showing the benefits of it. This question also acts as a catalyst to maintain them thinking about these newly learned processes and hopefully create a permanent place in their mind.

## Runout Worksheet

Total indicated runout (TIR) is the focus for the second symbolic dimensioning worksheet in Appendix J. This was chosen as TIR is very common among any type of turned part and is critical to consider in rotating assemblies. Following along with the simplicity goal of the project, the first idea for teaching runout was focused on a very basic example. To give the students hands on experience with this type of call out the questions would be paired with measuring of a turned part. They would be supplied with a dial test indicator, V-block, and a shaft with eccentric ends. A short explanation would cover how to correctly use these tools to measure the runouts of each end of the shaft. This setup can be seen in Figure 20 as it was being tested in the metrology lab on a granite surface plate.

Figure 20: Measuring runout using a dial indicator and V-block.

The first question seen in Figure 21 related to this setup asks for students to record the runout they measured for each end of the shaft with respect to the datum. This ensures that the students are correctly using the measurement equipment and setting up the tools in the desired orientation. With the numbers recorded they are then asked to reference a drawing of the part (Appendix K) and either accept or reject it based on the callouts. This layout is designed to give them a very basic idea of what a quality assurance engineer may do to analyze a part for a manufacturing company.

Continuing with the block project drawing package, the following question asks the students to explain how they would set up the lathe pin on page 79 to minimize runout and achieve the desired tolerances in the drawing. This lines up well with the class, because following this assignment the students will be manufacturing this part and will hopefully be able to implement what they have learned from this worksheet.

1. Using the supplied drawing on the last page, measure features 1.A and 1.B and confirm if they will be accepted or not. Explain your reasoning.

| 1:A = | 1:B = |
|---|---|

Figure 21: The first question on the runout worksheet is focused on runout measurements.

Question 2 in Figure 22 asks students what types of parts or assemblies require low or minimal runout to operate correctly. The goal here is to get students thinking about the topic and how it could affect products they use or design so they are more likely to remember what they have learned. It is likely their answers for this problem will be widely varied, but this will transition well for a discussion at the end of class. Before the assignment is submitted, the teacher will ask students to give the examples they thought of. This will hopefully cover a wide range of parts and help students understand the importance of runout.

2. What types of parts or assemblies require low or minimized runout?

Figure 22: Problem 2 gets students thinking about the impact of this callout.

Finally, the assignment is closed with students answering what some best practices are in the shop to avoid runout. The ideal answer would be things like using a four jaw chuck over a three jaw or using a live center on long parts. Some students may not have enough experience to answer these questions, but that gives an opportunity for group members or class mates to explain the benefits of these practices.

As with the first worksheet, once the allotted time is up the instructor will use the last ten to fifteen minutes of the class to go over the question on the worksheet to ensure students understand the correct answers. This is critical to the learning process, because if students are allowed to complete the worksheet without correctly grasping the concepts it would be a waste of time. Ideally this explanation period will allow students to see the correct methods to use on each question and then be able to use that knowledge on future work. Faculty can also use this time to record which problems are causing recurring issues and then adjust the assignment to eliminate this confusion.

## Initial Testing - ME325 Machine Design

The second set of worksheets was designed around fitting into the lean manufacturing class taught over the summer. It would ideally prepared students enough so they could understand the updated tolerances and symbols on the block project when they machine it during the first week. The issue that stood out from this is, was project was set to be completed by the end of the spring semester. The group wanted to test the worksheet prior to this class so if errors were present they wouldn't propagate through to the machined parts.

To test the worksheets before the summer semester it was chosen to use the ME325 Machine Design course. This class consists of mainly students in their junior year and focuses on topics including fasteners, welds, and fatigue. Typical experience with drawings and the machine shop is very similar to the ME301 class. One major difference with the class is it contains eighty students versus the usual forty-five for a junior level class and closer to twenty for lab sections and Lean Manufacturing. This major difference was noted before the testing, but due to the time frame it was the most applicable course to test with. Issue were assumed to arise from the larger size, but it would be taken into account for updates.

Similar to the testing of the first worksheet, students were broken up into groups of two or three and encouraged to check answers with other groups. The true position basics reference sheet was handed out at the beginning of class and then stepped through to explain the concepts. Multiple questions came up during this time as some students were not able to grasp the concepts with just a verbal explanation. The overhead and whiteboard were used to create figures that could help the students understand the topics, especially the effects of maximum material condition on a true position callout. After covering the handout there was were still a large number of students with questions, but it was decided for them to start on the assignment and then questions could be asked when they encountered difficulty on the problems.

Surprisingly many students had issues with the first four problems that focused around making sure they understood the ideas of maximum and least material conditions. Ideally these questions would not have been the troublesome one, but based on the questions during the reference sheet explanation it may have confused them more than helped them. When answers the student's questions one on one it was noticed that many were overthinking the questions and trying to use the true position callout when all they needed was the diameter tolerances. Another issue that was seen at the same time was some students did not have any experience with tolerances beyond the common symmetric style, so they were unsure how to find the values when given a limit style tolerance. This is something that would need to be cleared up earlier on, ideally during the Solidworks class when drawings are covered.

Problem 5 was more successful as it didn't require as much understanding and could be easily completed with the reference sheet. Students understood most of the callout, but still had questions about the MMC portion since it wasn't well grasped early on. With a better introduction and visuals explaining the ideas of MMC this problem shouldn't cause many more issues.

Most of the class ended this worksheet attempting problem six due to time constraints, but many students did get started on it. Based on the supplied answers only a small percentage of the students were on track. Most still had issues with the ideas of maximum material condition and were having a hard time grasping the area created by true position. A small amount of groups were able to solve the problem, but this was done after one on one questions with the students and use of the hands-on tools. The first worksheet had multiple issues that stood out from this testing and would need to be addressed in adaptations and updates.

After forty five minutes the class was prompted to switch over to the second worksheet so they could get some experience with runout before the class ended. The class was shown the runout example shown in Figure 20 on the overhead so they had the necessary information for problem one. Originally this was planned to be done for each group in lean manufacturing, but that would have required too much time in the class of eighty. Most of the class was able to answer the first problem correctly after the example was explained and stepped through, but did require more time than expected. Conveying the idea of what runout is versus concentricity was difficult, so that would also need a visual to explain the difference.

To finish off the assignment the final three questions are more open ended and don’t have specific correct answers. They are meant to prompt students to think about how they would manufacture a part and what impact the newly learned material would have on that process. For the runout worksheet they would likely bring up things like shafts being turned on lathes that will have an application in a rotating assembly. The answers received from ME325 were very mixed as a large majority of the students did not have machine shop experience. For the transition to lean manufacturing this assignment would likely work well in the above state if it was given after the students started work in the shop on the block project. It may need to be modified to be given out at the beginning of the course and could include things like showing examples of runout on a lathe before working through the assignment.

The testing that was done in ME325 showed some major issues that would need to be corrected for these two worksheets to be successful in future classes. Accurately conveying the ideas of true position, maximum material condition, and total indicated runout requires more visuals than originally thought. Other topics like the variety of tolerance styles and symbols will need to be clarified before the assignments and hopefully implemented earlier on in courses such as ME301. These ideas are the building blocks of GD&T and without a strong understanding of them the material becomes much more difficult.

To support these worksheets in the upcoming lean manufacturing course, visuals out of the Boeing Training Manual were added on the topics of true position and maximum material condition. These figures would be displayed during the beginning of a class period, prior to starting the assignment. This would allow students to see the ideas being explained in the true position basics worksheet, versus just having them explained vocally.

These specific figures were chosen, because they are clear and concise while providing all the necessary information to accurate convey the topic. Plus, using premade figures from the reference material saved time by not having to create the visuals internally. The explanation for true position versus a coordinate dimensioning scheme can be seen earlier in Figure 11, while the visuals for runout and maximum material condition can be seen in Figures 23 and 24 respectively. The addition of these figures combined with a thorough explanation prior to second worksheet set should adequately prepare students for the assignments.

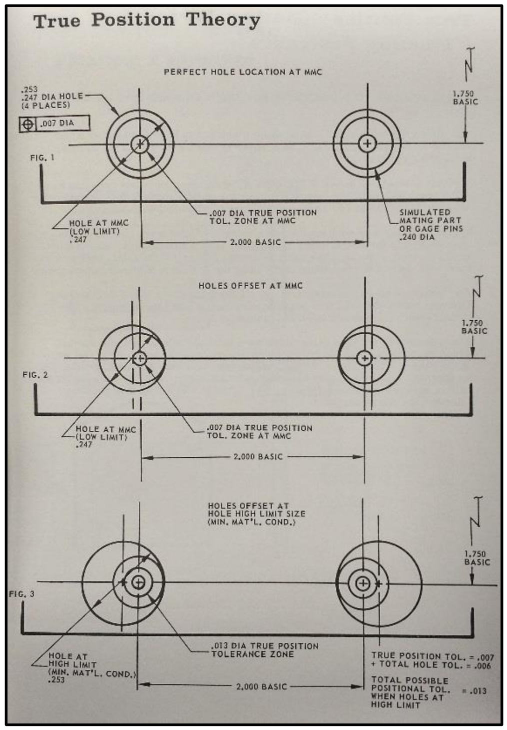



Figure 23: The Boeing training manual showing off the ideas of MMC and how it relates to true position.

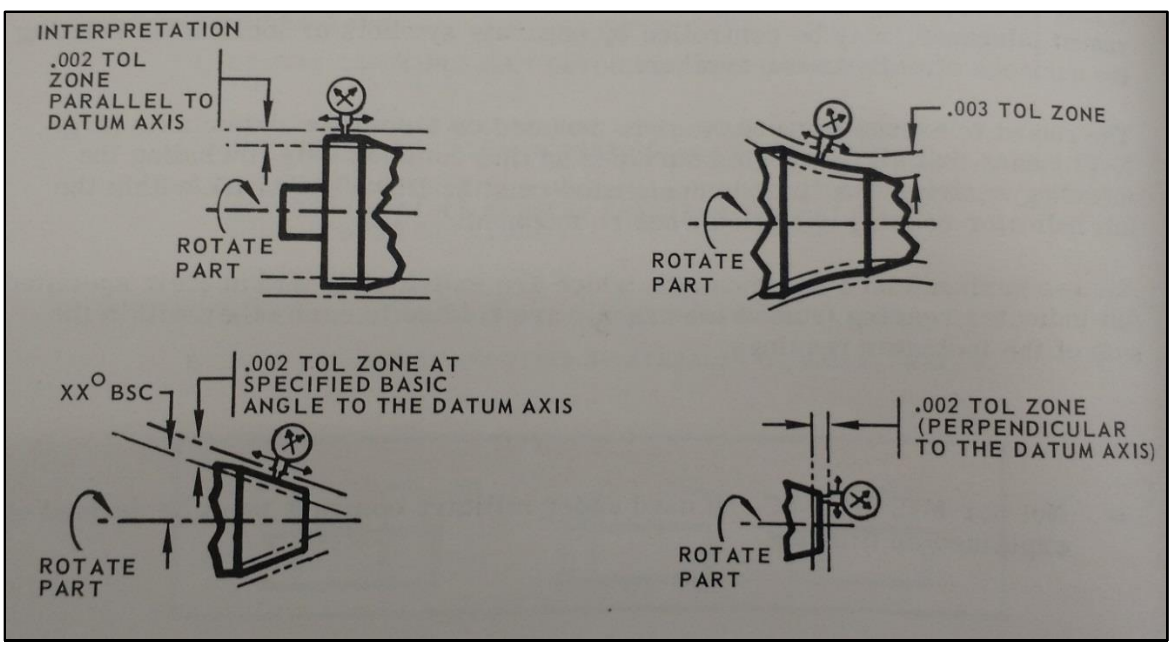



Figure 24: Runout being show in different setups supplied from the Boeing handbook.

Finally, the students would have access to copies of the true position and runout theory writing out of the Boeing manual. This would allow those students who learn better from reading a method that could work well with their learning style. The three pages of explanations on these topics can be seen in Appendix L. The writing does comply with the typical dry writing style that GD&T is known for, but there were no negatives seen with letting the students have access to it if they believed it could help them.

# CHAPTER 5: Conclusions

## Supportive Survey Data

This project showed that both alumni and industry professionals had seen a gap in recent college graduates with respect to manufacturing knowledge. Data collected from the surveys, direct emails, and in-person conversations all supported the idea of updating the Mechanical Engineering program to increase the manufacturing knowledge gained by students. This input drove the selection of GD&T as the area of focus for this project. It was a topic that repeatedly showed up during the surveys and it was not addressed outside of the machine shop prior to this work.

## Effectiveness of Implemented Teaching Tools

The teaching modules created during this project provided students in multiple classes with a basis of knowledge in the areas of dimensioning and tolerancing. This understanding will ideally act as a catalyst for the students to continue learning about new manufacturing topics throughout their education and into their careers. The full impact of the work done will not be seen until the upcoming Solidworks and Lean Manufacturing classes have concluded and the students are able to apply their new knowledge to future projects in Senior Design and beyond.

The hands-on tools used to teach the ideas of true position, maximum material condition, and runout will continue to act as examples available to students to ensure their understanding of the topics. This understanding will be critical for any students that wish to venture into a field of work with any connection to manufacturing. Their proper understanding of the concepts will be able to be seen in their future project through proper application of tolerances and realistic expectations of manufacturing methods.

Finally, the project shows that the faculty, students, and alumni at the University of Idaho are driven to continuously improve their programs to make them as strong as possible. This drive is something that separates the graduates of the Mechanical Engineering program from the competition and shows employers that our students are prepared for industry.

## Future Work

Many of the professionals surveyed mentioned recent graduates were also lacking a breadth of knowledge on the topic of manufacturing and it is not something directly covered in the current curriculum. Many recent graduates do not have the ability to make an educated guess as to how certain parts are manufactured based upon their complexity and quantity required.

Design for manufacturing was another topic that was frequently mentioned by the respondents. They said it was common to see designs that accomplished the goals of a project, but would be incredibly difficult and expensive to manufacture. This is commonly seen at U of I when students first start designing prototypes for their projects, before gaining experience in the machine shop. Many have never used machine tools before, so they have no idea of the time required or the limitations of the machines. Typically after spending some time with graduate student mentors in the machine shop the students learn what needs to be considered before manufacturing a part, but this experience is not guaranteed for graduates.

Lastly a subject that was mentioned far more than the group expected was the idea of business operations and how they relate to manufacturing. Ideas like calculated risks and return on investment for capital equipment purchases were brought up multiple times. There is a small amount of this taught during the thermal energy systems course, but it does not cover all of the topics mentioned by respondents.

All of these subjects are very important, but due to time constraints they were not directly covered by this work. An ideal solution to these shortcomings would be creating a complete class that could cover all of these topics in detail. The hurdle that would have to be overcome with this idea would be finding time in the current curriculum where it could fit.

# References

Allen, N. B. (2002). *The Stirling Engine Project - Fabrication and Experiments for Sophomore Laboratory*. Moscow, ID: University of Idaho.

American Society of Mechanical Engineers. (1966). *Dimensioning and Tolerancing for Engineering Drawings.* New York, NY: American Society of Mechanical Engineers.

Boeing Company, The. (1965). *Geometric & Positional Dimensioning and Tolerancing.*

Dobie, H. (1942). *Plus or Minus: A Study of the Application of Tolerances in Machining Operations.* Rugeley, Staffordshire, UK: The Draughtsman Publishing Co.

Henzold, G. (2006). *Geometric Dimensioning and Tolerancing for Design, Manufacturing and Inspection.* Burlington, MA: John Wiley and Sons Ltd.

Industrial Press. (2000). *Machinery's Handbook 26.* New York, NY: Industrial Press Inc.

Kalpakjuan, S., & Schmid, S. R. (2006). *Manufacturing Engineering and Technology*. Upper Saddle River, NJ: Pearson Education Inc.

Miller, M. H., & Weinmann, K. J. (2002). *Improving the Relevance of Manufacturing in a Mechanical Engineering Curriculum.* American Society fo Engineering Education.

Ramers, D. (2002). *Integrating Manufacturing Projects into Mechanical Engineering Programs.* Montreal, Canada: Paper Presented at 2002 Annual Conference.

Spurlin, J. E., Rajala, S. A., & Lavelle, J. P. (2007). *Designing Better Engineering Education Through Assessment.* Sterling, Virginia: Stylus Publishing.

# Appendix A: Survey Data 1

Responses to the question: "If you were hiring a new engineering employee what skills and knowledge in manufacturing would you be looking for?"

"Knowledge of engineering fundamentals – basic mechanics, thermodynamics, fluids, materials, engineering mathematics with a hint of chemistry thrown in. Some basic electronics are wonderful, with knowledge or even better skills in doing programming. Now comes the more interesting parts – understanding tolerances, the world of variability (nothing is exact in the world and when it isn't how do you handle it?) How to conduct a good experiment, especially being able to design an experiment to get an answer to a hypothesis. Understanding operations. We have a process we use for new products that are brought to us called "Design for eXcellence" (DfX). That process looks at many aspects of the design of a product beyond function and cost. Here's the wiki link for the topic: https://en.wikipedia.org/wiki/Design_for_X What this process emphasizes and seems to be missing for an engineer when they are in the manufacturing environment is the operations side of manufacturing. Every engineer seems to think manufacturing is processes to fabricate parts/components and methods to assemble those parts and components into a product. It is much, much more than that, and ultimate requires a systems view of what I call productization."

"Excellent communication skills. Curiosity and a willingness to ask questions. Basic data analysis and statistics skills (e.g. using Excel, and stat's software). Basic skills in Problem Solving tools and Process Improvement techniques. Ability to write a comprehensive and understandable technical report. Able to present information and ideas to a small group of colleagues. Current "best practices" in engineering design applications (e.g. what is going on with 3D printing, latest developments in production methods, etc). CAD/CAM skills, PCB layouts, Programming (depending on industry/degree)."

"I do not hire based off manufacturing knowledge. I hire based off work ethic and dealing with problems head on. Most of the time I do not get a choice on what manufacturing skillset I get, so we train in house what is needed. We teach new employees about machining, CNC plasma/laser cutters, weldments, and very simple tolerancing."

"Experience with lean/agile design paradigms and how to mix with waterfall approaches. Experience with P&ID and GD&T also required."

"Lean and six sigma training are key for a company cranking out a matured product as every cost/waste is scrutinized. I have worked on countless projects to reduce assembly time to decrease overall cost. Hands on experience with developing check fixtures for components & assemblies would also be a good skill to have."

"Ideally we would look for manufacturing experience and lean manufacturing. Experience pool is small for our geographical area so always train."

"I would look for someone who understands the different methods for manufacturing to adapt to different production rates. For example, a car fender currently needs a very expensive die set to manufacture, but you wouldn't use that same methodology to build airplanes simply because the cost of the tools would be too great. Or, with today's 3D printing technology, some airplane parts may be able to be cost effective if printed, simply due to the cost of setup and tools versus the additive manufacturing method cost. A person who then understands how the actual design would differ is what I'd look for."

"The ability to work safely in a manufacturing/industrial environment. Ability to read and create manufacturing drawings. Any real experience working in an actual industrial environment. Some understanding of how things are machined is sometimes useful. Any experience or course work that would help with the understanding of product moving through the manufacturing process. As I work at a paper mill some people it takes them a while to grasp that it is a continuous process that doesn't stop and product goes straight from one process to the next."

"Over the last three years we've hired seven engineers out of college and noticed a recurring trend regardless of what school they attended. Though their CAD skills are adequate for 3D parametric modeling, none are able to create professional quality prints or grasp the complexity of GD&T. I understand each company may have it's own methods and standards but even at a basic level these skills are lacking. Secondly, it is difficult to find new graduates with practical hydraulics training or know how basic flow dividers work."

"I would look for the same skills that I learned...the ability to design with how we are planning to manufacture in mind. My biggest frustration with new hires is their lack of understanding of manufacturing processes such as welding, machining, and sometimes even simple bolted assemblies. Simple knowledge about these subjects go a long way, and I feel that the Lean Manufacturing course was one of the best ones that taught these skills. When I was still there this class was only offered in the summer...I would like to see it offered during the school year as well."

# Appendix B: International Manufacturing Trade Show Survey Data

“Geometric Dimensioning and Tolerancing along with some knowledge of mold making.”

“Improved knowledge of scheduling for projects of any size, idea of time requirements for different operations, and the basics of GD&T.”

“More classes focused on manufacturing topics. Hands-on experience is critical. Willing to work with a range of people and not think floor workers or machinist are below them.”

“Hands-on experience trumps everything. Willing to change their ways to improve themselves.”

“A wide knowledge of different processes. Don’t need to know all the details of each, but understand the basics and how they can be beneficial to you. Know when and where to go to learn more if needed.”

“Be open to learn from the shop manager or machinist. They have a huge amount of knowledge that is a resource. Don’t think of yourself as being above them.”

“Hands-on experience with machines and design for manufacturability is very important.”

“The hands-on experience people get from growing up around mechanical projects. Kids that grow up on a farm learn to weld and repair stuff instead of just buying another. That knowledge and skillset is very beneficial.”

“Hand drawing experience, plus a solid understanding of tolerances and when/how to use them.”

"Automation and CAM experience. Knowing how to improve processes and increase throughput. Open to learning new programs or controls."

"Hands-on shop experience grinding tools, using mills and lathes, programming CNC tools, and associated floor work. Knowing what goes into the work done in the machine shop."

"Hands-on experience in machine shop is key to working in the machine tool industry and beneficial to anyone going into manufacturing."

"Machining apprenticeship is the perfect lead in to engineering, but would require a large amount of time invested into themselves."

# Appendix C: Profile of Survey Data Respondents

| Graduation Year | Degree | Field | Top 3 | Additions |
|---|---|---|---|---|
| 2008 | BSME | Manufacturing | Social Skills, Hands On, DFM | Automation/PLCS |
| 1995 | PHD | Capital Equipment Design and | Team Work, Business, Social Skills | Mindset of learning and growth |
| 1961 | BSME | Energy Storage and Clean Energy | Team Work, Project management, DFM | Operations management, qc |
| 1986 | BSME | Aerospace | Team Work, Hands on, CAM | FEA |
| 2007 | MSME | Industrial Electronics Design | Hands On, CAM, GDT | FEA |
| 1975 | MSME | Chemical/Mechanical | DFM, Project Management, Team Work | Self Starter |
| 1973 | MEME | Product Design | GDT, Project management, Business | Regulations, product testing |
| 2010 | MSME | Project Management | Project management, Team Work, Business | Outside of required class projects |
| 2013 | MSME | Manufacturing | project management, Team work, hands on | Communications, verbal and written |
| 1990 | BSME | Automotive | Project Management, CAM, DFM | Systems Understanding |
| NA | NA | Manufacturing | Team Work, Project management, DFM | Innovation |
| 2010 | BSME | Supply Chain Management | Team Work, DFM, Project management | Flexible and coachable. |
| 1975 | BSAgE | Electronics Manufacturing | DFM, Business, Team Work | Understaning Variability and people |
| 1985 | Pre-Law Poly Sci | Operations management | Project Management, GDT, Hands on | Work Ethic/Character |
| 2006 | MSME | Cleaning Equipment | DFM, Team Work, PM | Simulations, Proof of concept |
| 2009 | MSME | Medical | GDT, Team Work, Social Skills | Risk Assessment |
| 2011 | MSME | Aerospace | DFM, Team Work, PM | Reliable |
| 2004 | MSME | Outdoor Equipment | PM, Social Skills,Team Work | Self Starter |
| 2012 | MSME | Manufacturing | Hands On, Team Work, Social Skills | Ambition for their own hobbies |
| 2014 | BSME | Aerospace | DFM, Team Work, Social Skills | Applying technical skills to real world |
| 1985 | BSME | Manufacturing | Team Work, Hands on, DFM | |
| 2004 | BSME | Aerospace | Team Work, GDT, Hands On | Global understanding |
| 2012 | BSME | Aerospace | Hands On, PM, DFM | Work Ethic/Character |

| | | | | |
|---|---|---|---|---|
| 2015 | BSME | Web Development | PM, Business, Social Skills | |
| 2015 | BSME | Industrial Electronics Design | Team Work, GDT, Hands On | Working with other disciplines |
| On going | BSME | Facilities Eng. | DGM, GDT, PM | Manufacturing environment exp. |
| 2006 | BSME | Manufacturing | DFM, Team Work, PM | |
| 1993 | BSME | Engineering Technology | Hands On, Team Work, PM | Variation |
| 2011 | MSME | Aeronautical | PM, CAM, Business | Material Processing, Manufacturing Processes |
| 2015 | MSME | Consulting | Team Work, Hands On, PM | |
| 1993 | MSME | Aerospace | Hands On, Social Skills, DFM | Writing Skills |
| 2003 | BSME | Manfuacturing Quality | DFM, Hands On, Team Work | CAD |
| 1988 | BSME | Aerospace | DFM, Hands On, GDT | Mixing school with real world |
| 2013 | BSME | Aerospace | Hands on, DFM, Team Work | |
| 2014 | MSME | Tooling | Social Skills, Buisness, CAM | Work Ethic, Prioritze tasks |
| 2012 | BSME | Astro-physics | CAM, Team Work, GDT | Vendor Relations |
| 2015 | BSME | Nuclear | Team Work, PM, Social Skills | Understanding technical books |
| 2011 | BSME | Nuclear Waste Handling, Hydropower | Hands On, DFM, GDT | Design for cost |
| 2011 | BSME | Heavy Industry Design | PM, DFM, Team Work | Time Management |
| 2007 | PHD | Academia | DFM, PM, Hands On | Troubleshooting |

# Appendix D: Coordinate Dimensioning Worksheet

## GD&T Block Project Worksheet

(Assume Non-Specified Dimensions Are Nominal)

1. What is the maximum possible center to center distance between the holes using dimensions 7.A and 7.B?

______________________________

2. What are the maximum and minimum distances between datum A and edge 5.B?

______________________________

3. Is the diameter dimension for all of the grooves on part 1-04 the same? Explain.

______________________________

______________________________

4. Which edges are most likely to contact first when part 1-01 and part 1-02 are mated. (Assume they are perfectly concentric. Use dimensions 3A, 3B, 4A, and 4B.)

______________________________

______________________________

5. Is it possible for edge 8.C to contact the bottom block prior to edge 8.D when the parts are assembled correctly and everything is in tolerance?

______________________________

6. What are the maximum and minimum distances that edge 7.E can lie from datum A on page 7? Are there any issues with how this edge is dimensioned?

7. With regards to the last two problems, is there a way that these issues could be avoided or at least improved upon?

8. Is it possible to have a fit issue with the pin location at 7.F and the slip fit hole at 8.E? If so, what is the issue? Assume pin and hole diameters are exact.

9. Imagine an instance of this assembly where the true manufactured dimensions are given below. Assuming all other dimensions are at their stated ideal dimension, will the lathe pin fit through the blocks? If not why and what could be done to alleviate the problem?

| | Description | Measurement |
|---|---|---|
| 5.A | Lathe Pin Diameter | 0.5020” |

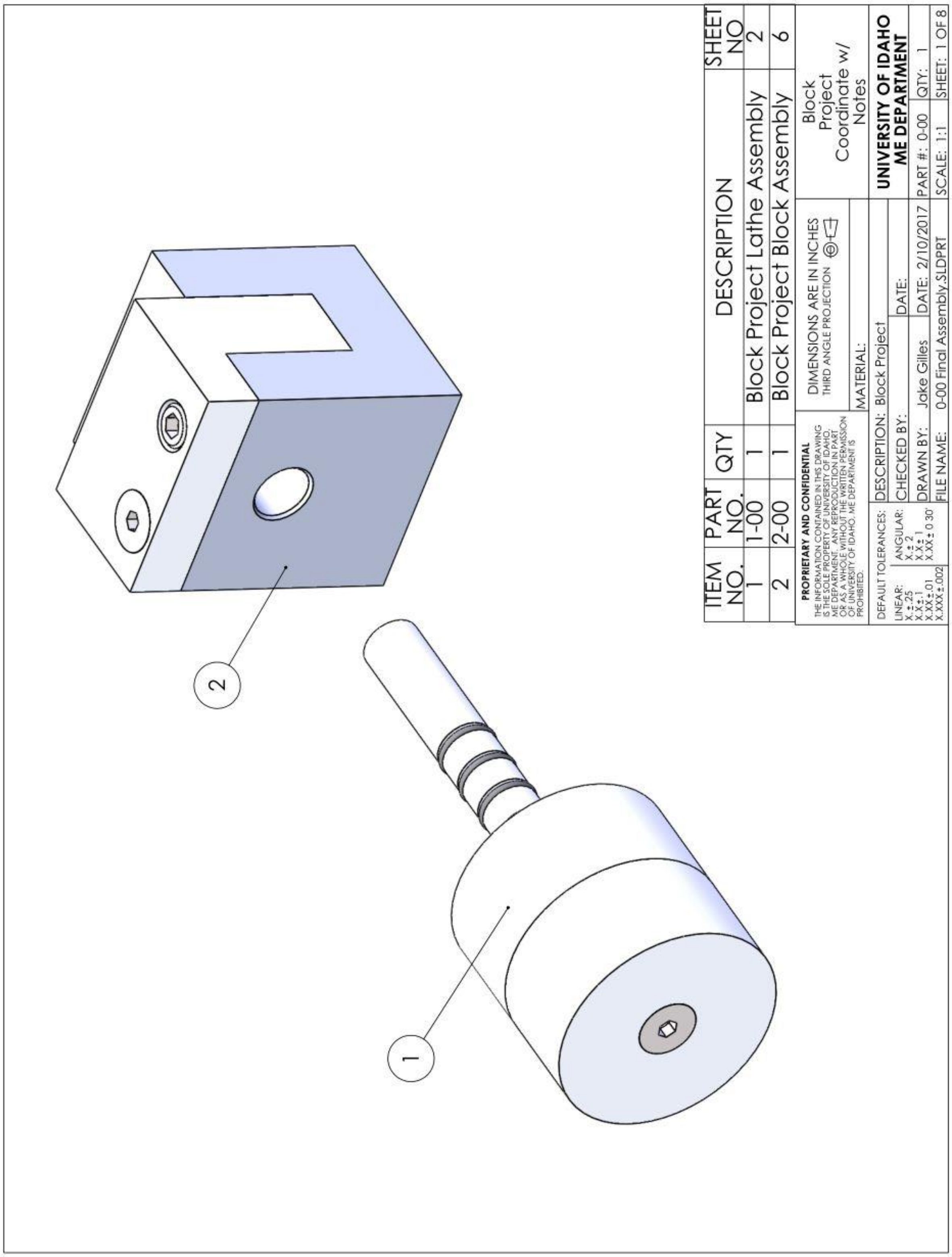
| | | |
|---|---|---|
| 7.C | Pin Hole Location | 0.6260” |
| 8.A | Pin Hole Location | 0.6250” |
| 8.B | Shoulder Height | 1.2470” |
| 8.F, 7.H | Reamed Hole Diameter | .5050” |

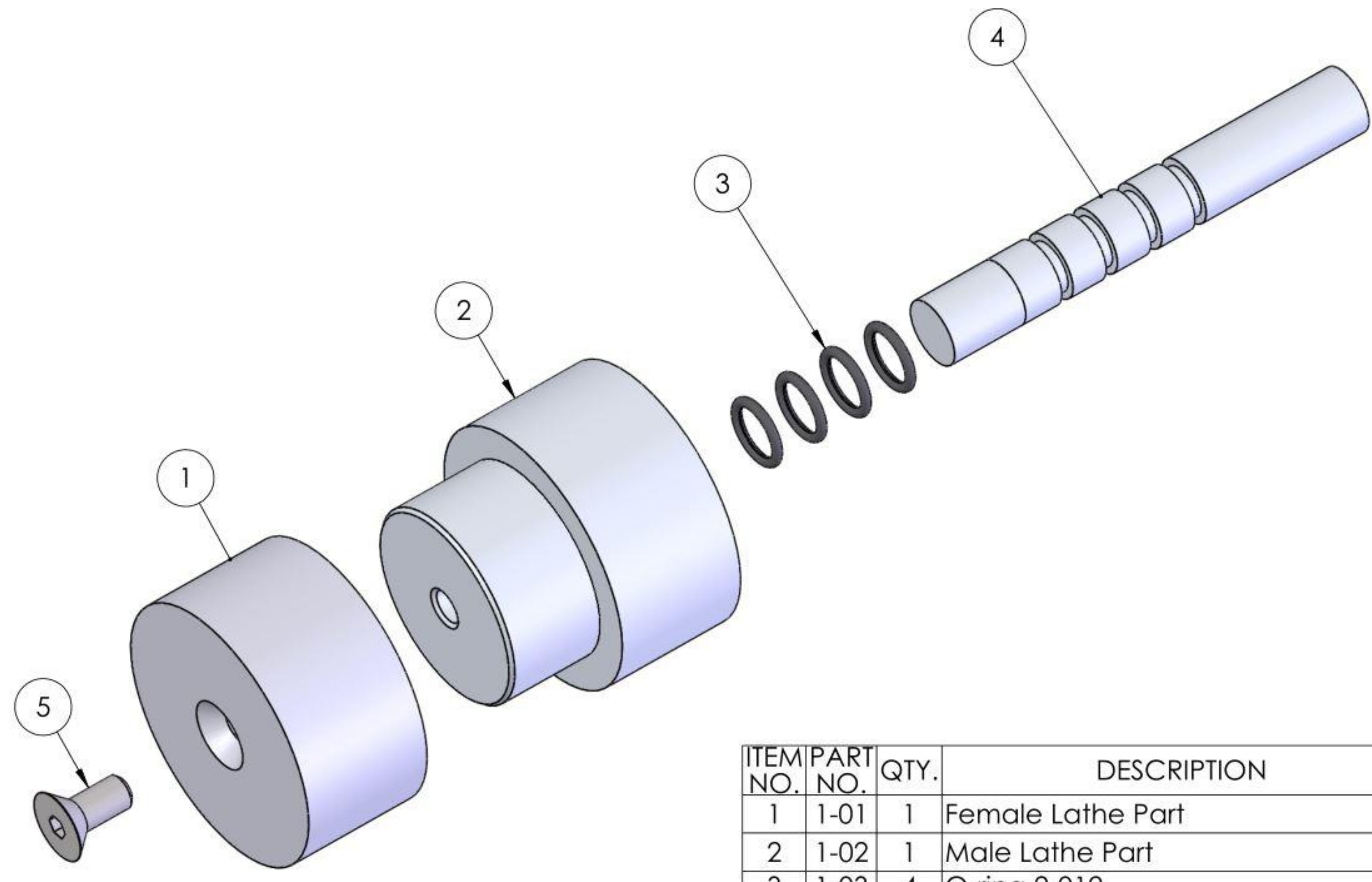
10. The above question is only considering variations in one axis. What happens when the other axis perpendicular to the hole depth changes?

11. What reoccurring issues can you see with this drawing package and dimensioning scheme?

12. In the future when you are creating drawing packages for your parts and assemblies how will you avoid these types of problems?

# Appendix E: Block Project Drawing Package – Coordinate Dimensioning






| ITEM NO. | PART NO. | QTY. | DESCRIPTION | SHEET NO. |
|---|---|---|---|---|
| 1 | 1-01 | 1 | Female Lathe Part | 3 |
| 2 | 1-02 | 1 | Male Lathe Part | 4 |
| 3 | 1-03 | 4 | O-ring 2-012 | -- |
| 4 | 1-04 | 1 | Lathe Pin | 5 |
| 5 | 1-05 | 1 | 1/4"-20 x 3/8" CS Screw | -- |

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DIMENSIONS ARE IN INCHES
THIRD ANGLE PROJECTION

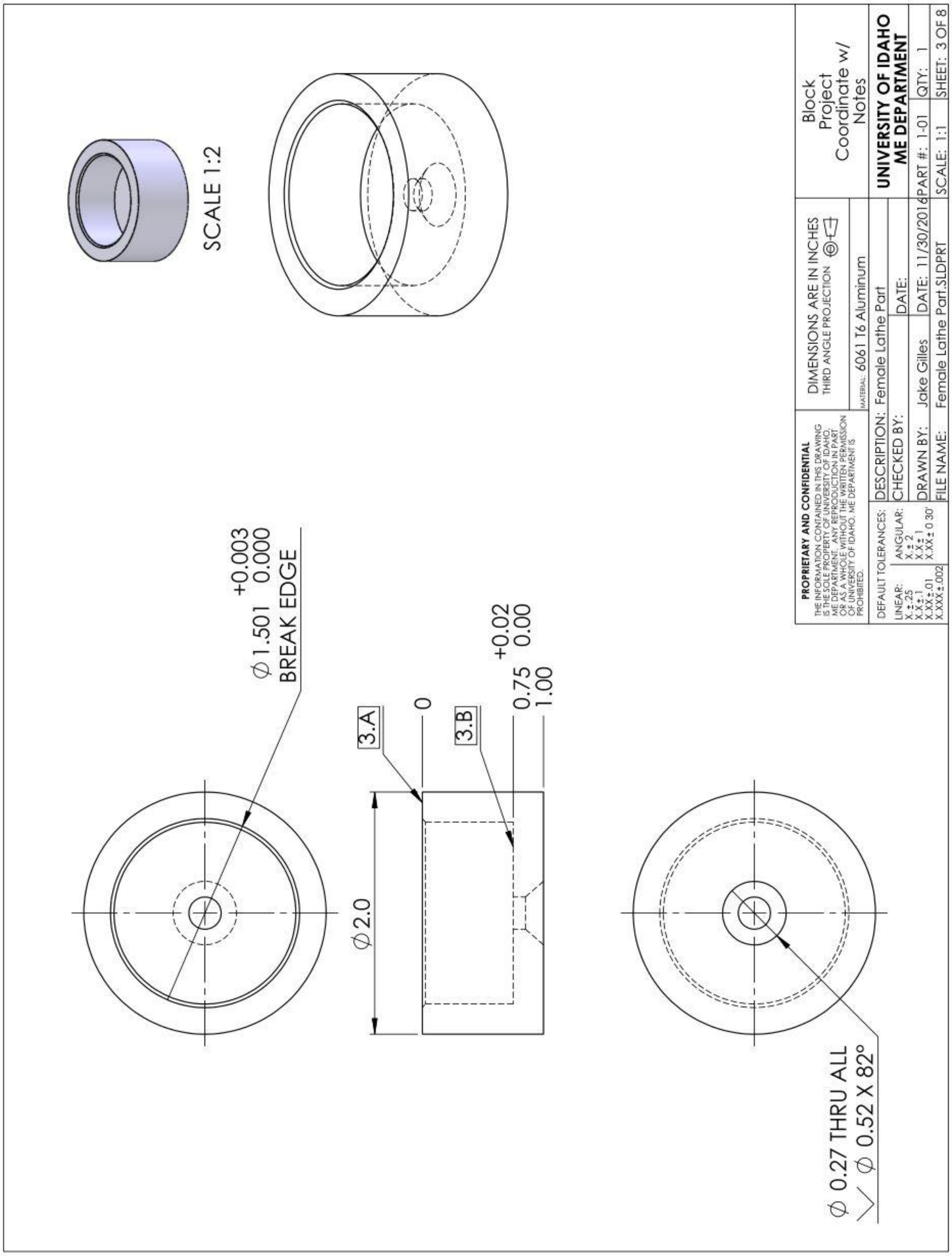
MATERIAL:

Block Project Coordinate w/ Notes

DEFAULT TOLERANCES:
LINEAR: X.±.25 X.X±.1 X.XX±.01 X.XXX±.002
ANGULAR: X.±2 X.X±1 X.XX±0 30'

DESCRIPTION: Block Project Lathe Assembly
CHECKED BY: DATE:
DRAWN BY: Jake Gilles DATE: 2/10/2017
FILE NAME: 1-00 Lathe Assembly.SLDPRT

**UNIVERSITY OF IDAHO**
**ME DEPARTMENT**
PART #: 1-00 QTY: 1
SCALE: 1:1 SHEET: 2 OF 8


SCALE 1:2
Ø 1.501 +0.003 0.000
BREAK EDGE
3.A
3.B
0
0.75 +0.02 0.00
1.00
Ø 2.0
Ø 0.27 THRU ALL
⌵ Ø 0.52 X 82°
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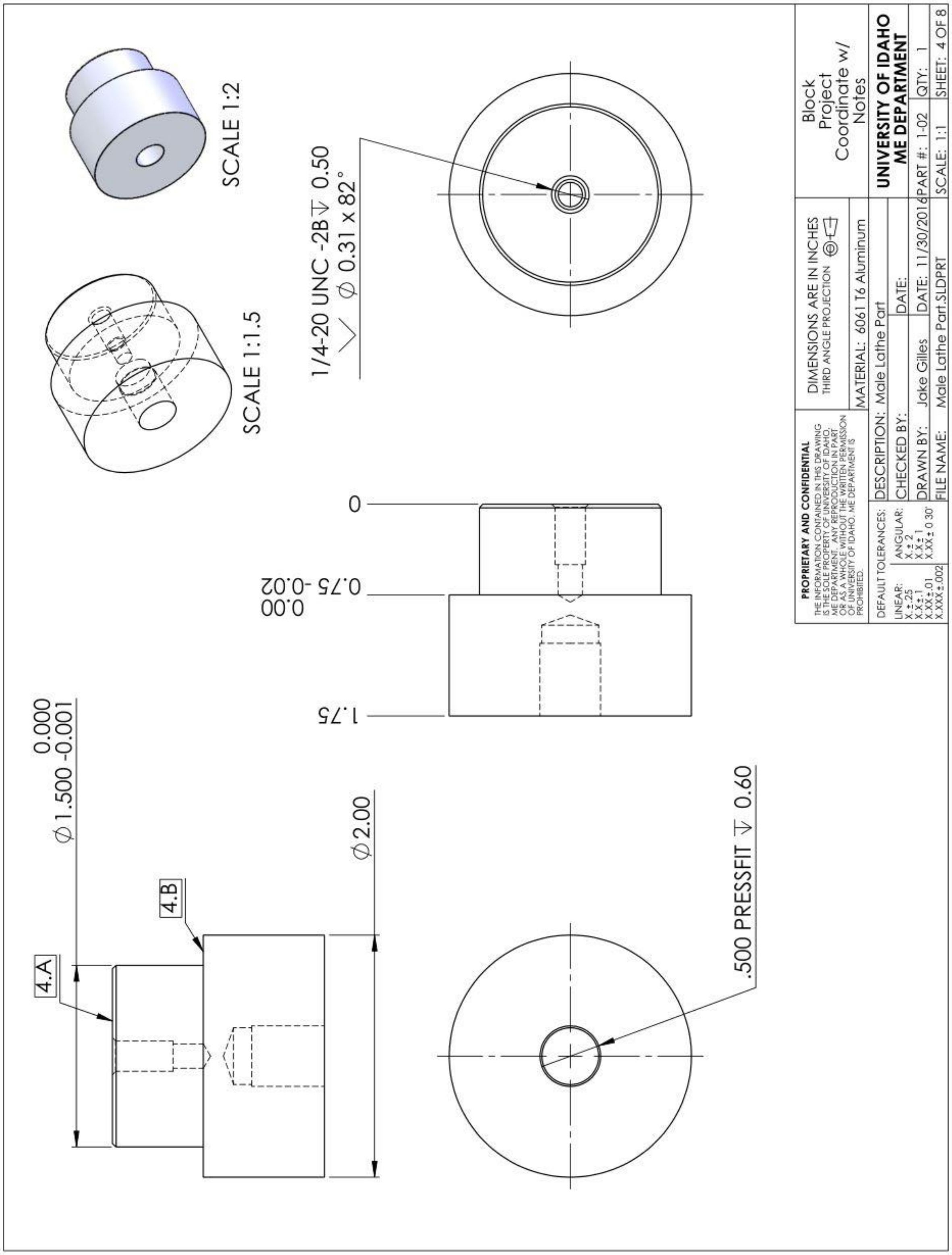
DIMENSIONS ARE IN INCHES
THIRD ANGLE PROJECTION
MATERIAL: 6061 T6 Aluminum
Block Project Coordinate w/ Notes
DEFAULT TOLERANCES:
LINEAR: X. ±.25 X.X ±.1 X.XX ±.01 X.XXX ±.002
ANGULAR: X. ± 2 X.X ± 1 X.XX ± 0 30'
DESCRIPTION: Female Lathe Part
CHECKED BY:
DATE:
DRAWN BY: Jake Gilles
DATE: 11/30/2016
FILE NAME: Female Lathe Part.SLDPRT
UNIVERSITY OF IDAHO
ME DEPARTMENT
PART #: 1-01
QTY: 1
SCALE: 1:1
SHEET: 3 OF 8



SCALE 1:2
SCALE 1:1.5
1/4-20 UNC -2B ↧ 0.50
⌵ ⌀ 0.31 x 82°
0
0.75 -0.02
0.00
1.75
0.000
⌀1.500 -0.001
4.A
4.B
⌀2.00
.500 PRESSFIT ↧ 0.60
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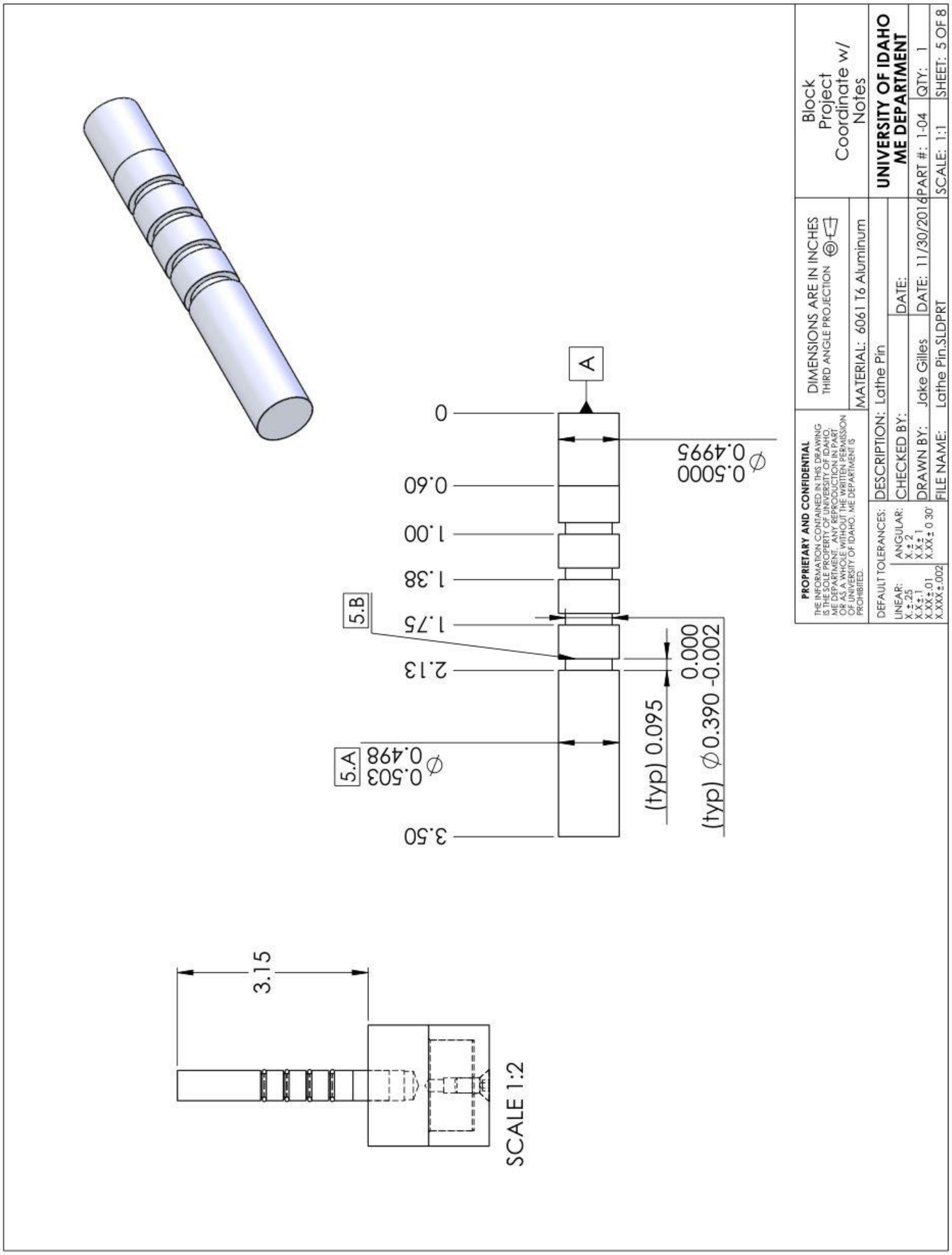
DIMENSIONS ARE IN INCHES
THIRD ANGLE PROJECTION
MATERIAL: 6061 T6 Aluminum
Block Project Coordinate w/ Notes
DEFAULT TOLERANCES:
LINEAR: X. ±.25 X.X±.1 X.XX±.01 X.XXX±.002
ANGULAR: X. ±2 X.X±1 X.XX± 0 30'
DESCRIPTION: Male Lathe Part
CHECKED BY:
DATE:
DRAWN BY: Jake Gilles
DATE: 11/30/2016
FILE NAME: Male Lathe Part.SLDPRT
UNIVERSITY OF IDAHO ME DEPARTMENT
PART #: 1-02
QTY: 1
SCALE: 1:1
SHEET: 4 OF 8


0
0.60
1.00
1.38
1.75
2.13
3.50
A
5.B
5.A
Ø 0.5000
0.4995
Ø 0.503
0.498
(typ) 0.095
(typ) Ø0.390 0.000
-0.002
3.15
SCALE 1:2
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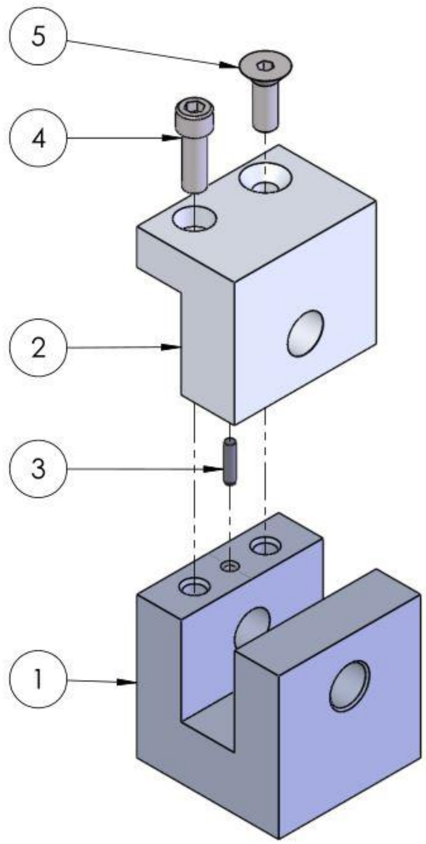
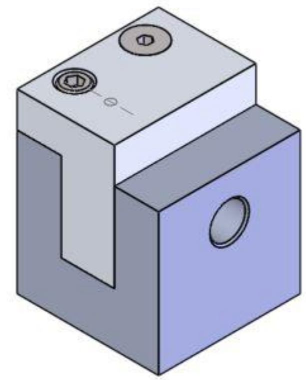
DIMENSIONS ARE IN INCHES
THIRD ANGLE PROJECTION
MATERIAL: 6061 T6 Aluminum
DEFAULT TOLERANCES:
LINEAR: X ±.25 X.X ±.1 X.XX ±.01 X.XXX ±.002
ANGULAR: X ±2 X.X ±1 X.XX ± 0 30'
DESCRIPTION: Lathe Pin
CHECKED BY:
DATE:
DRAWN BY: Jake Gilles
DATE: 11/30/2016
FILE NAME: Lathe Pin.SLDPRT
Block Project Coordinate w/ Notes
UNIVERSITY OF IDAHO
ME DEPARTMENT
PART #: 1-04
QTY: 1
SCALE: 1:1
SHEET: 5 OF 8



| ITEM NO. | PART NO | QTY. | DESCRIPTION | SHEET NO |
|---|---|---|---|---|
| 1 | 2-01 | 1 | Bottom Block | 7 |
| 2 | 2-02 | 1 | Top Block | 8 |
| 3 | 2-03 | 1 | 0.125 x 0.5 Dowel Pin | --- |
| 4 | 2-04 | 1 | 1/4"-20 x 3/8" SHCS | --- |
| 5 | 2-05 | 1 | 1/4"-20 x 3/8" CS Screw | --- |

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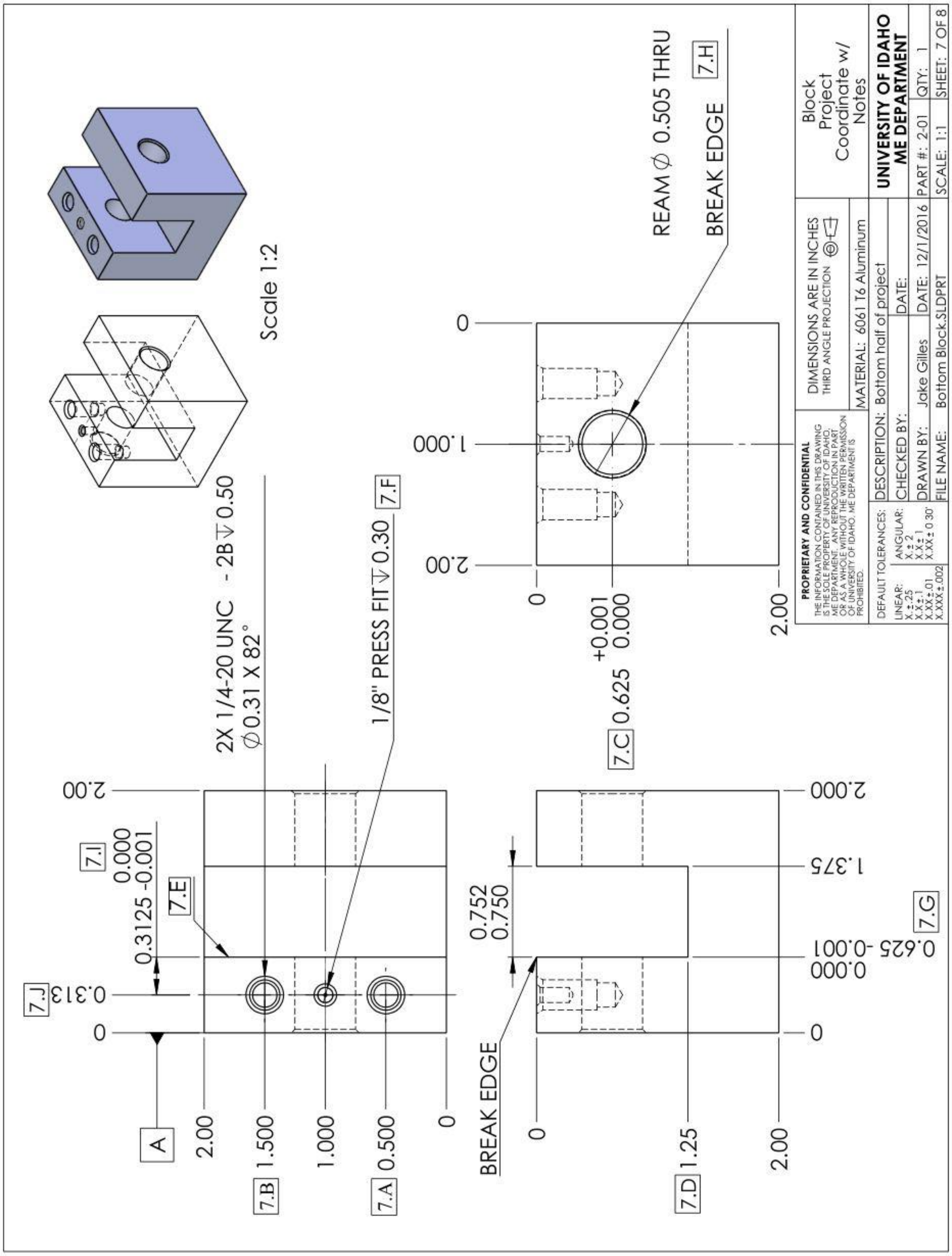
DIMENSIONS ARE IN INCHES
THIRD ANGLE PROJECTION

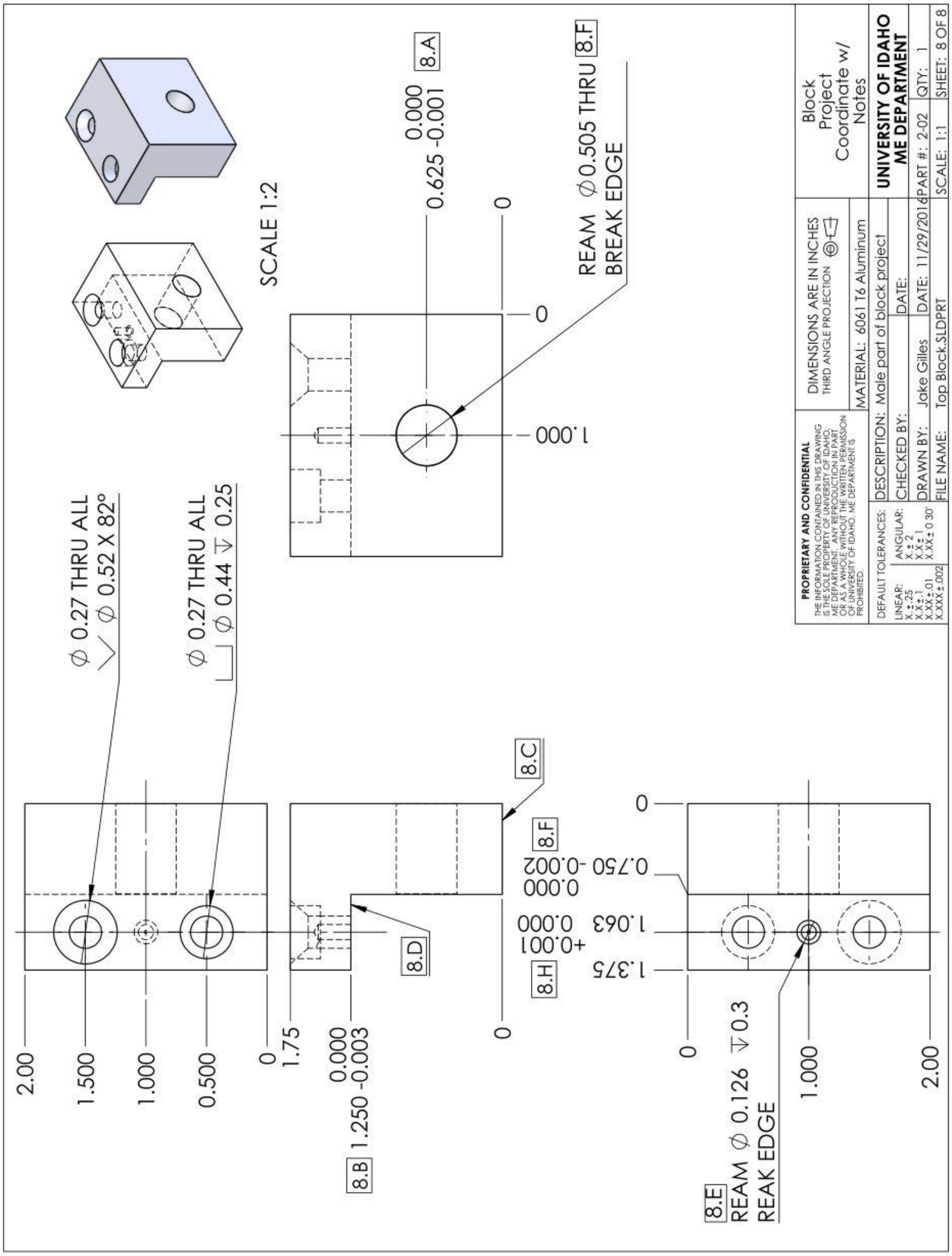
MATERIAL:

Block Project Coordinate w/ Notes

DEFAULT TOLERANCES:
LINEAR: X. ±.25, X.X±.1, X.XX±.01, X.XXX±.002
ANGULAR: X.± 2, X.X± 1, X.XX± 0 30'

| | | | |
|---|---|---|---|
| DESCRIPTION: Block Project Block Assembly | | UNIVERSITY OF IDAHO ME DEPARTMENT | |
| CHECKED BY: | DATE: | | |
| DRAWN BY: Jake Gilles | DATE: 2/10/2017 | PART #: 2-00 | QTY: 1 |
| FILE NAME: 2-00 Block Assembly.SLDPRT | | SCALE: 1:1.5 | SHEET: 6 OF 8 |


REAM Ø 0.505 THRU 7.H
BREAK EDGE
Scale 1:2
2X 1/4-20 UNC - 2B ⊽ 0.50
Ø 0.31 X 82°
1/8" PRESS FIT ⊽ 0.30 7.F
7.C 0.625 +0.001 0.000
7.E
7.I 0.3125 0.000 -0.001
7.J 0.313
A
7.B 1.500
7.A 0.500
7.D 1.25
7.G 0.625 0.000 -0.001
0.752 0.750
1.375
2.000
PROPRIETARY AND CONFIDENTIAL
DIMENSIONS ARE IN INCHES
THIRD ANGLE PROJECTION
MATERIAL: 6061 T6 Aluminum
DESCRIPTION: Bottom half of project
CHECKED BY:
DATE:
DRAWN BY: Jake Gilles
DATE: 12/1/2016
FILE NAME: Bottom Block.SLDPRT
DEFAULT TOLERANCES:
Block Project Coordinate w/ Notes
UNIVERSITY OF IDAHO ME DEPARTMENT
PART #: 2-01
QTY: 1
SCALE: 1:1
SHEET: 7 OF 8


⌀ 0.27 THRU ALL
⌵ ⌀ 0.52 X 82°
⌀ 0.27 THRU ALL
⌴ ⌀ 0.44 ↧ 0.25
SCALE 1:2
0.000
0.625 -0.001
8.A
REAM ⌀0.505 THRU 8.F
BREAK EDGE
0
1.000
2.00
1.500
1.000
0.500
0
1.75
0.000
8.B 1.250 -0.003
8.C
8.D
8.F
8.H
0.750 -0.002
0.000
+0.001
0.000
1.063
1.375
8.E
REAM ⌀ 0.126 ↧ 0.3
REAK EDGE
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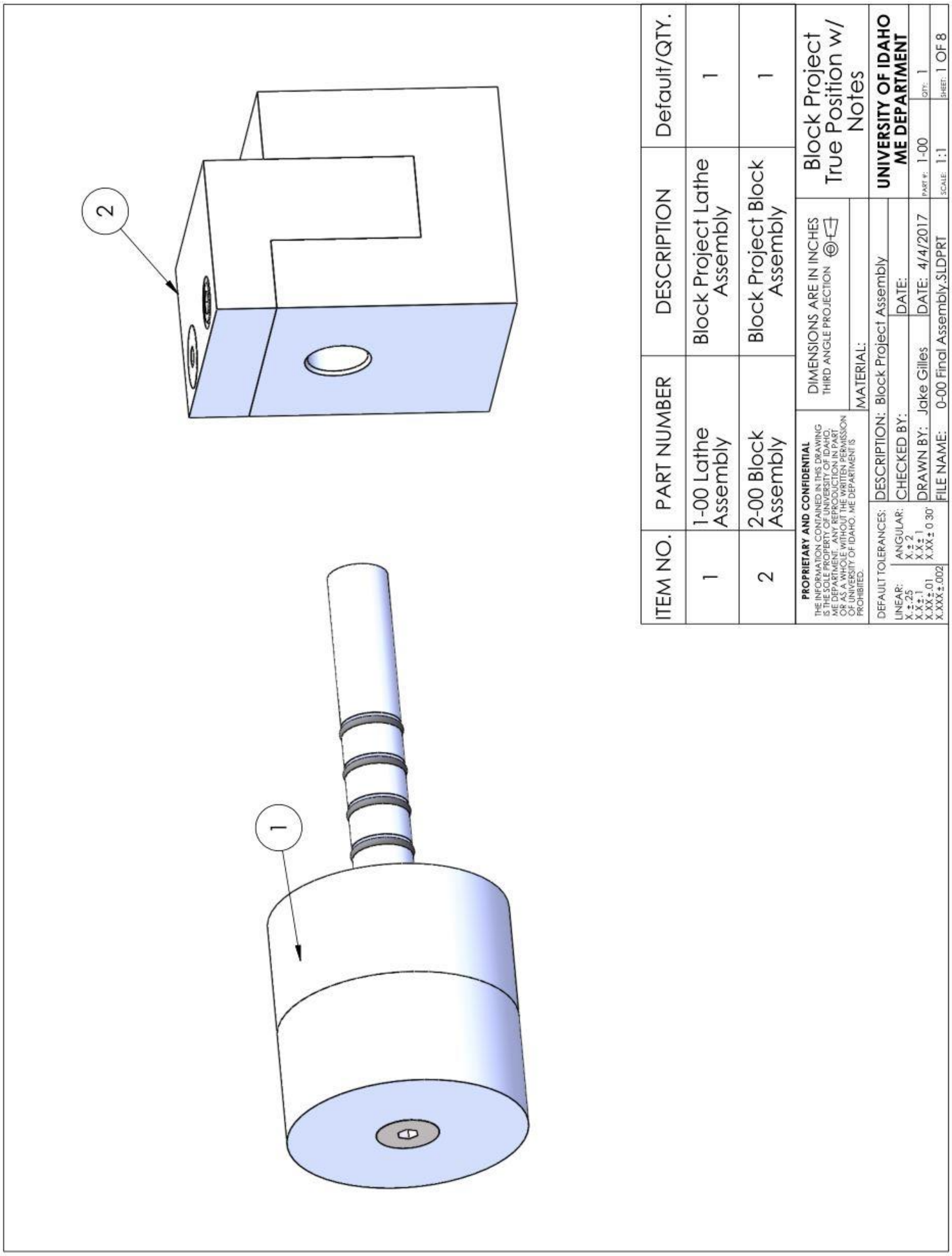
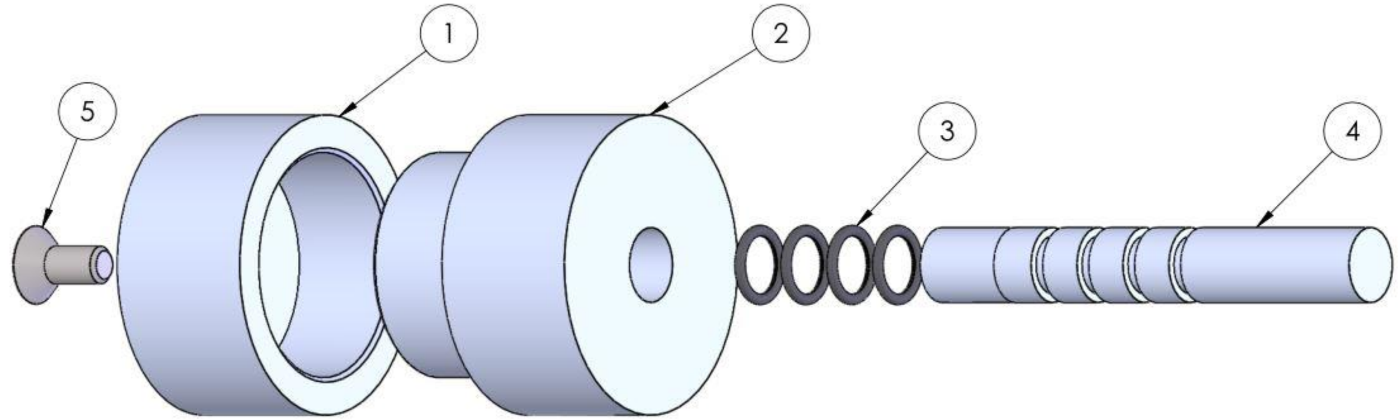
DIMENSIONS ARE IN INCHES
THIRD ANGLE PROJECTION
MATERIAL: 6061 T6 Aluminum
DEFAULT TOLERANCES:
LINEAR: X ±.25 X.X ±.1 X.XX ±.01 X.XXX ±.002
ANGULAR: X ±2 X.X ±1 X.XX ±0 30'
DESCRIPTION: Male part of block project
CHECKED BY:
DATE:
DRAWN BY: Jake Gilles
DATE: 11/29/2016
FILE NAME: Top Block.SLDPRT
Block Project Coordinate w/ Notes
UNIVERSITY OF IDAHO
ME DEPARTMENT
PART #: 2-02
QTY: 1
SCALE: 1:1
SHEET: 8 OF 8

# Appendix F: Block Project Drawing Package – Symbolic Dimensioning






| ITEM NO. | PART NUMBER | DESCRIPTION | Default/ QTY. |
|---|---|---|---|
| 1 | 1-01 | Female Lathe Part | 1 |
| 2 | 1-02 | Male Lathe Part | 1 |
| 3 | 9452K21 | O-ring | 4 |
| 4 | 1-04 | Lathe Pin | 1 |
| 5 | SCHCSCREW 0.25-20x0.5625x0.5625-HX-N | Cap Screw | 1 |

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DIMENSIONS ARE IN INCHES
THIRD ANGLE PROJECTION

MATERIAL: Multiple

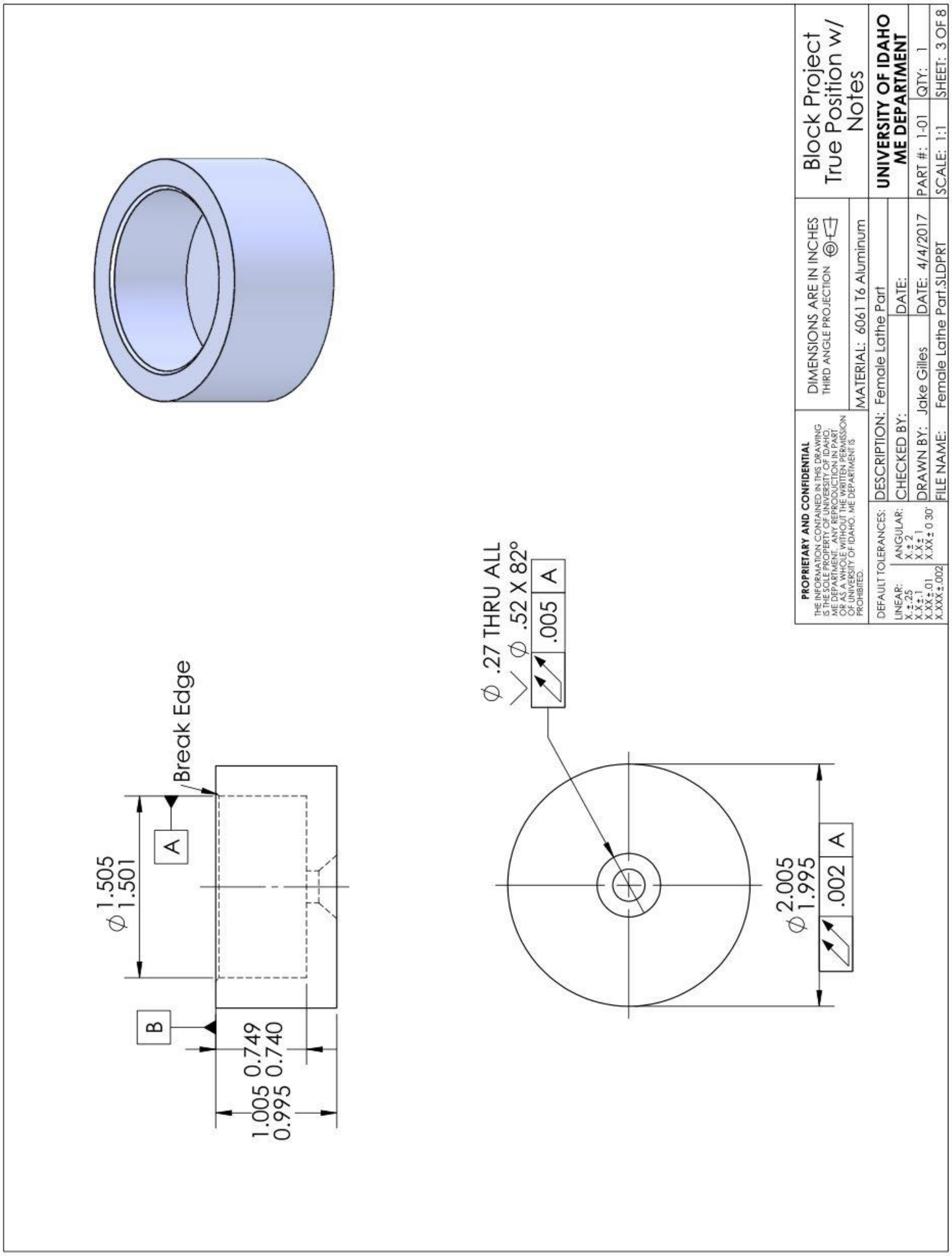
Block Project True Position w/ Notes

DEFAULT TOLERANCES:
LINEAR: X.±.25, X.X±.1, X.XX±.01, X.XXX±.002
ANGULAR: X.±2, X.X±1, X.XX±0 30'

DESCRIPTION: Lathe Subassembly
CHECKED BY: DATE:
DRAWN BY: Jake Gilles DATE: 4/4/2017
FILE NAME: 1-00 Lathe Assembly.SLDPRT

**UNIVERSITY OF IDAHO ME DEPARTMENT**

PART #: 1-00 QTY: 1
SCALE: 1:1 SHEET: 2 OF 8



Ø 1.505
1.501
A
Break Edge
B
1.005 0.749
0.995 0.740
Ø .27 THRU ALL
⌵ Ø .52 X 82°
.005 | A
Ø 2.005
1.995
.002 | A
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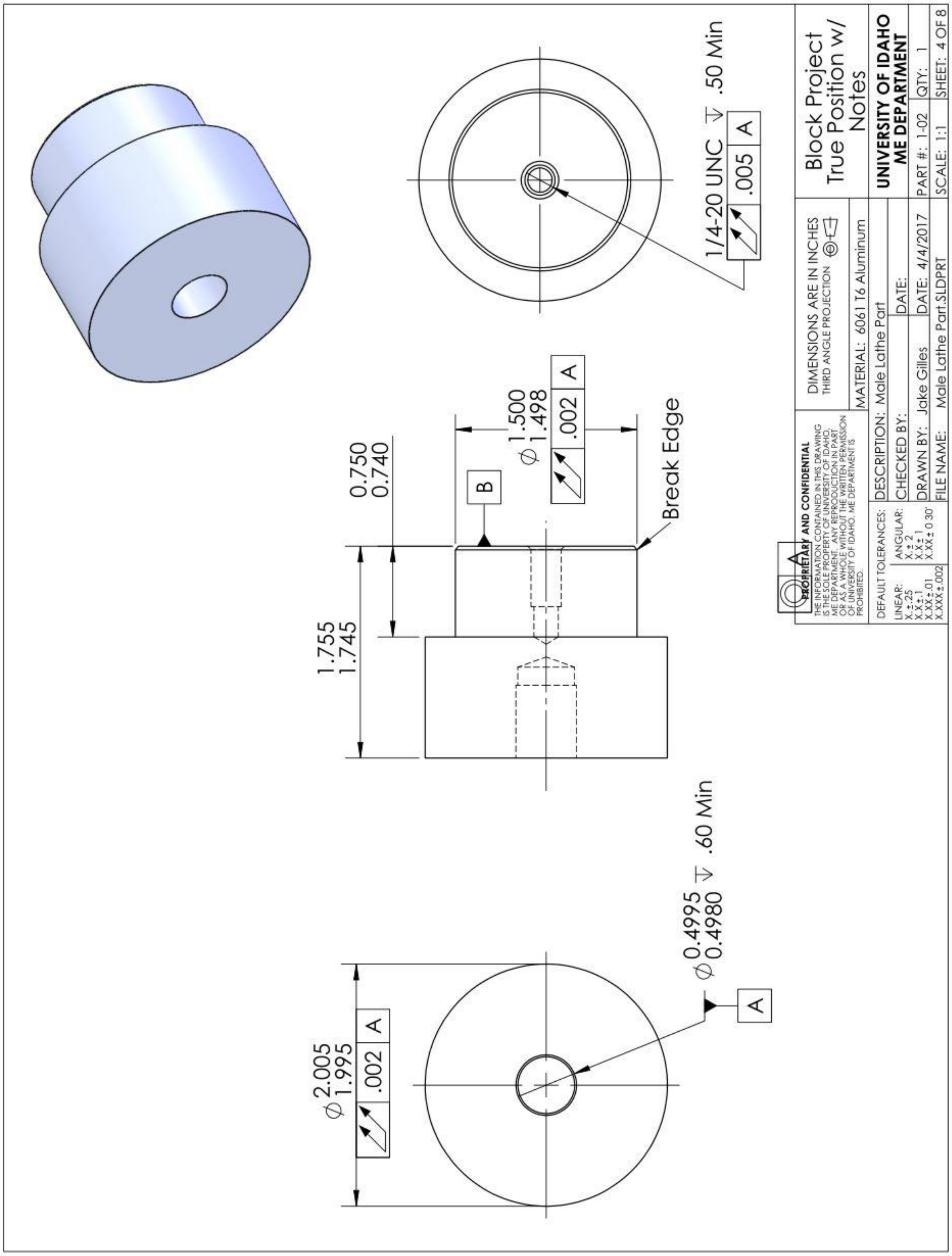
DIMENSIONS ARE IN INCHES
THIRD ANGLE PROJECTION
Block Project True Position w/ Notes
MATERIAL: 6061 T6 Aluminum
DEFAULT TOLERANCES:
DESCRIPTION: Female Lathe Part
UNIVERSITY OF IDAHO
ME DEPARTMENT
LINEAR: X. ±.25 X.X ±.1 X.XX ±.01 X.XXX ±.002
ANGULAR: X. ±2 X.X ±1 X.XX ± 0 30'
CHECKED BY:
DATE:
DRAWN BY: Jake Gilles
DATE: 4/4/2017
PART #: 1-01
QTY: 1
FILE NAME: Female Lathe Part.SLDPRT
SCALE: 1:1
SHEET: 3 OF 8



Ø 2.005 1.995
.002 A
Ø 0.4995 0.4980 ↧ .60 Min
A
1.755 1.745
0.750 0.740
B
Ø 1.500 1.498
.002 A
Break Edge
1/4-20 UNC ↧ .50 Min
.005 A
A
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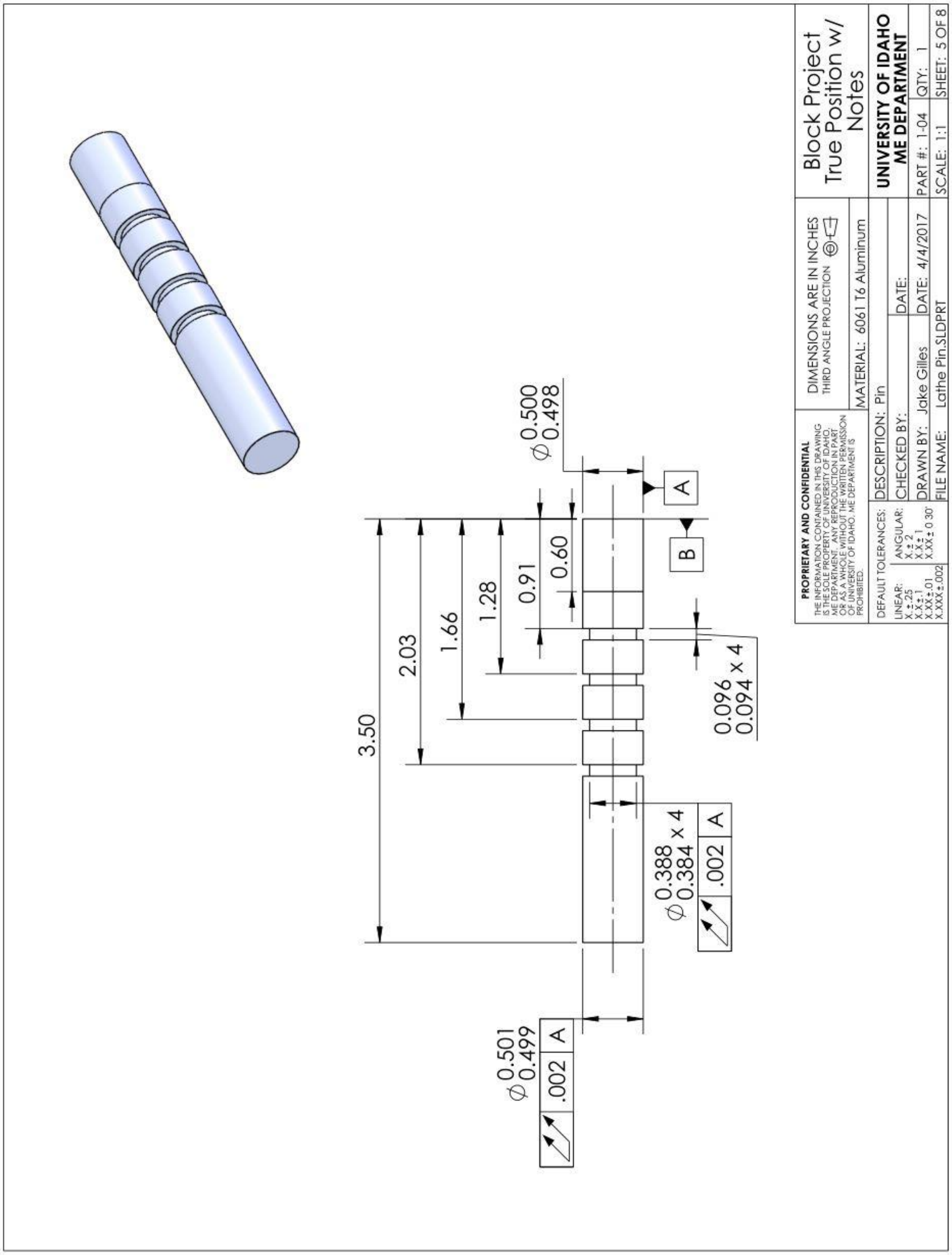
DIMENSIONS ARE IN INCHES
THIRD ANGLE PROJECTION
Block Project True Position w/ Notes
DEFAULT TOLERANCES:
LINEAR: X. ±.25 X.X ±.1 X.XX ±.01 X.XXX ±.002
ANGULAR: X. ±2 X.X ±1 X.XX ± 0 30'
MATERIAL: 6061 T6 Aluminum
DESCRIPTION: Male Lathe Part
CHECKED BY:
DATE:
DRAWN BY: Jake Gilles
DATE: 4/4/2017
FILE NAME: Male Lathe Part.SLDPRT
UNIVERSITY OF IDAHO ME DEPARTMENT
PART #: 1-02
QTY: 1
SCALE: 1:1
SHEET: 4 OF 8


Ø 0.501 0.499
.002 A
3.50
2.03
1.66
1.28
0.91
0.60
Ø 0.500 0.498
A
B
Ø 0.388 0.384 x 4
.002 A
0.096 0.094 x 4
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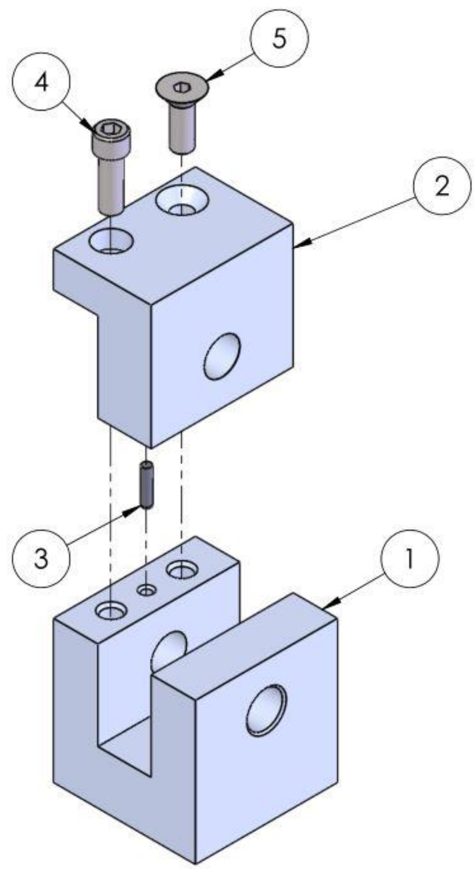
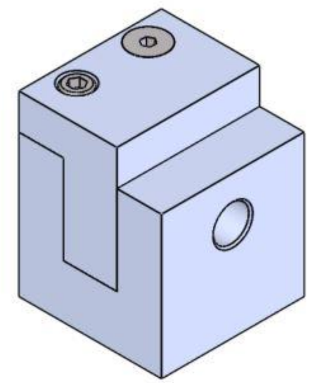
DIMENSIONS ARE IN INCHES
THIRD ANGLE PROJECTION
MATERIAL: 6061 T6 Aluminum
DEFAULT TOLERANCES:
LINEAR:
ANGULAR:
DESCRIPTION: Pin
CHECKED BY:
DATE:
DRAWN BY: Jake Gilles
DATE: 4/4/2017
FILE NAME: Lathe Pin.SLDPRT
Block Project True Position w/ Notes
UNIVERSITY OF IDAHO ME DEPARTMENT
PART #: 1-04
QTY: 1
SCALE: 1:1
SHEET: 5 OF 8



| ITEM NO. | PART NUMBER | DESCRIPTION | QTY. |
|---|---|---|---|
| 1 | 2-01 | Bottom half of project | 1 |
| 2 | 2-02 | Male part of block project | 1 |
| 3 | 2-03 | 1/8" x 1/4" Dowel Pin | 1 |
| 4 | HX-SHCS 0.25-20x0.75x0.75-N | Socket Head Cap Screw | 1 |
| 5 | SCHCSCREW 0.25-20x0.75x0.75-HX-N | Countersunk Screw | 1 |

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DIMENSIONS ARE IN INCHES
THIRD ANGLE PROJECTION

MATERIAL: Multiple

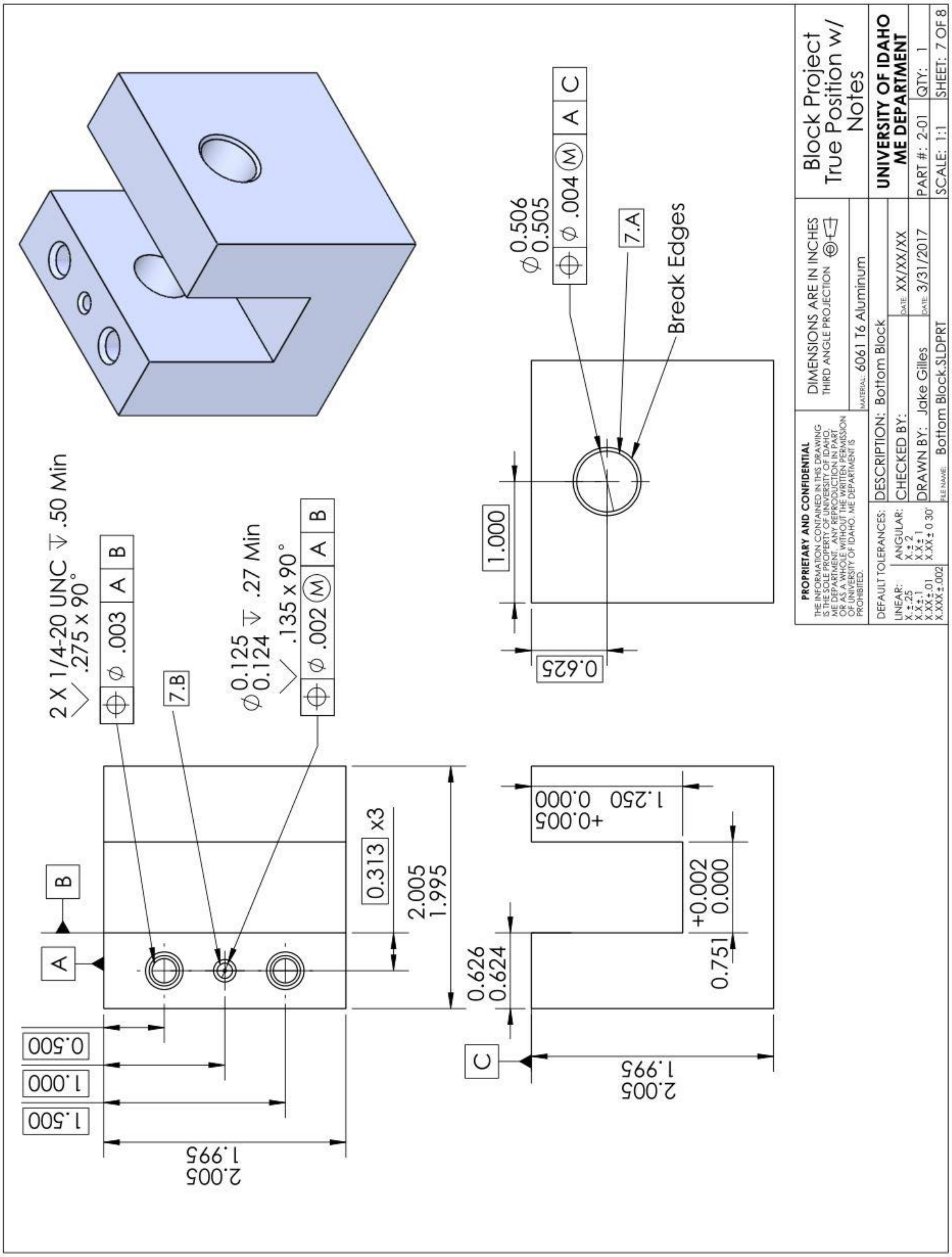
Block Project True Position w/ Notes

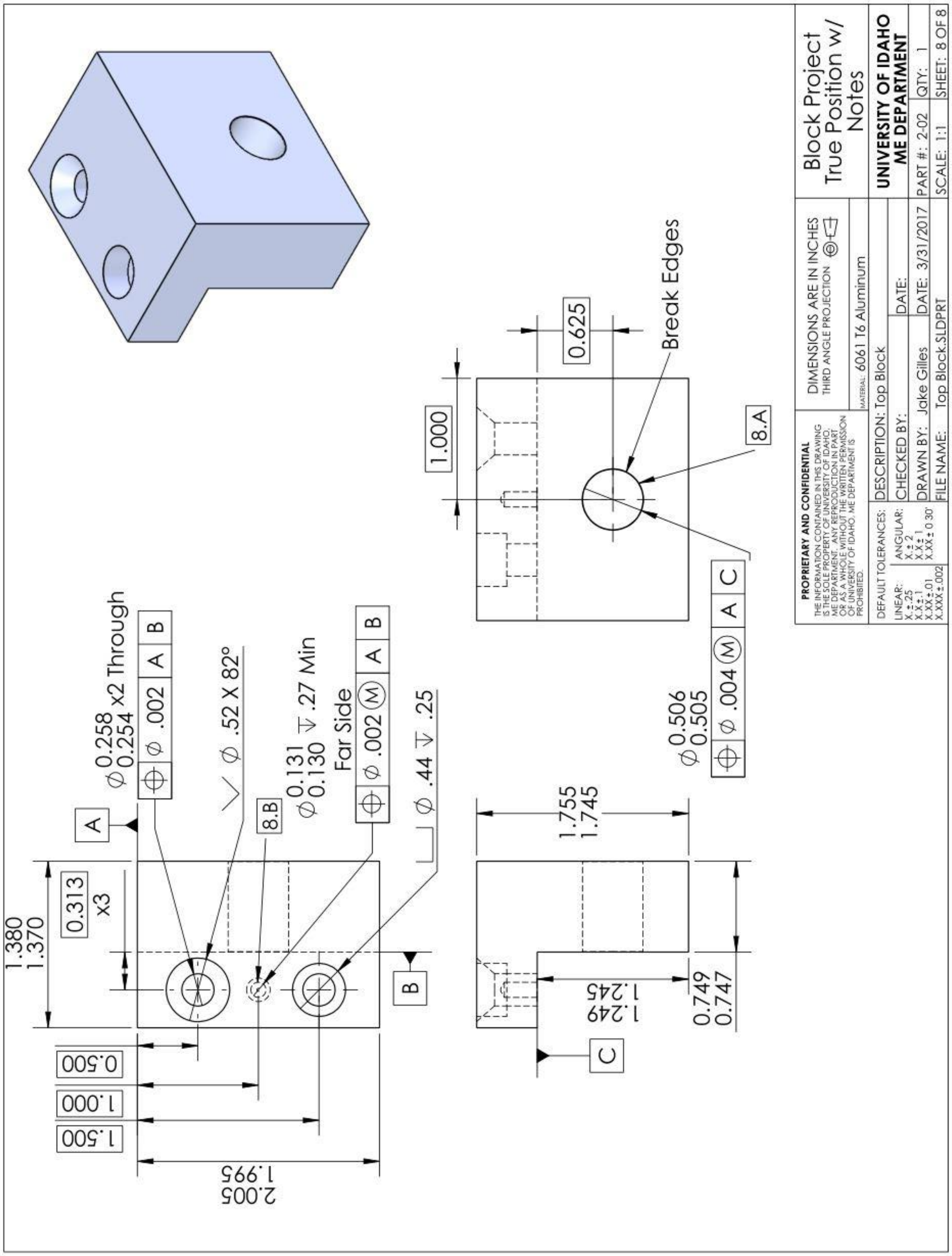
DEFAULT TOLERANCES:
LINEAR: X.±.25 X.X±.1 X.XX±.01 X.XXX±.002
ANGULAR: X.± 2 X.X± 1 X.XX± 0 30'

DESCRIPTION: Mill Subassembly
CHECKED BY: DATE:
DRAWN BY: Jake Gilles DATE: 4/4/2017
FILE NAME: 2-00 Block Assembly.SLDPRT

**UNIVERSITY OF IDAHO ME DEPARTMENT**

PART #: 2-00 QTY: 1
SCALE: 1:1.5 SHEET: 6 OF 8


2 X 1/4-20 UNC ⊽ .50 Min
.275 x 90°
⌖ ⌀ .003 | A | B
7.B
⌀ 0.125 / 0.124 ⊽ .27 Min
.135 x 90°
⌖ ⌀ .002 Ⓜ | A | B
A
B
C
0.500
1.000
1.500
2.005 / 1.995
0.313 x3
2.005 / 1.995
0.626 / 0.624
+0.005 / 0.000 1.250
+0.002 / 0.000 0.751
2.005 / 1.995
0.625
1.000
⌀ 0.506 / 0.505
⌖ ⌀ .004 Ⓜ | A | C
7.A
Break Edges
PROPRIETARY AND CONFIDENTIAL
DIMENSIONS ARE IN INCHES
THIRD ANGLE PROJECTION
MATERIAL: 6061 T6 Aluminum
DESCRIPTION: Bottom Block
CHECKED BY:
DATE: XX/XX/XX
DRAWN BY: Jake Gilles
DATE: 3/31/2017
FILE NAME: Bottom Block.SLDPRT
DEFAULT TOLERANCES:
LINEAR: X. ±.25 X.X±.1 X.XX±.01 X.XXX±.002
ANGULAR: X. ±2 X.X±1 X.XX±0 30'
Block Project True Position w/ Notes
UNIVERSITY OF IDAHO
ME DEPARTMENT
PART #: 2-01
QTY: 1
SCALE: 1:1
SHEET: 7 OF 8


Block Project
True Position w/
Notes
UNIVERSITY OF IDAHO
ME DEPARTMENT
PART #: 2-02
QTY: 1
SCALE: 1:1
SHEET: 8 OF 8
DIMENSIONS ARE IN INCHES
THIRD ANGLE PROJECTION
MATERIAL: 6061 T6 Aluminum
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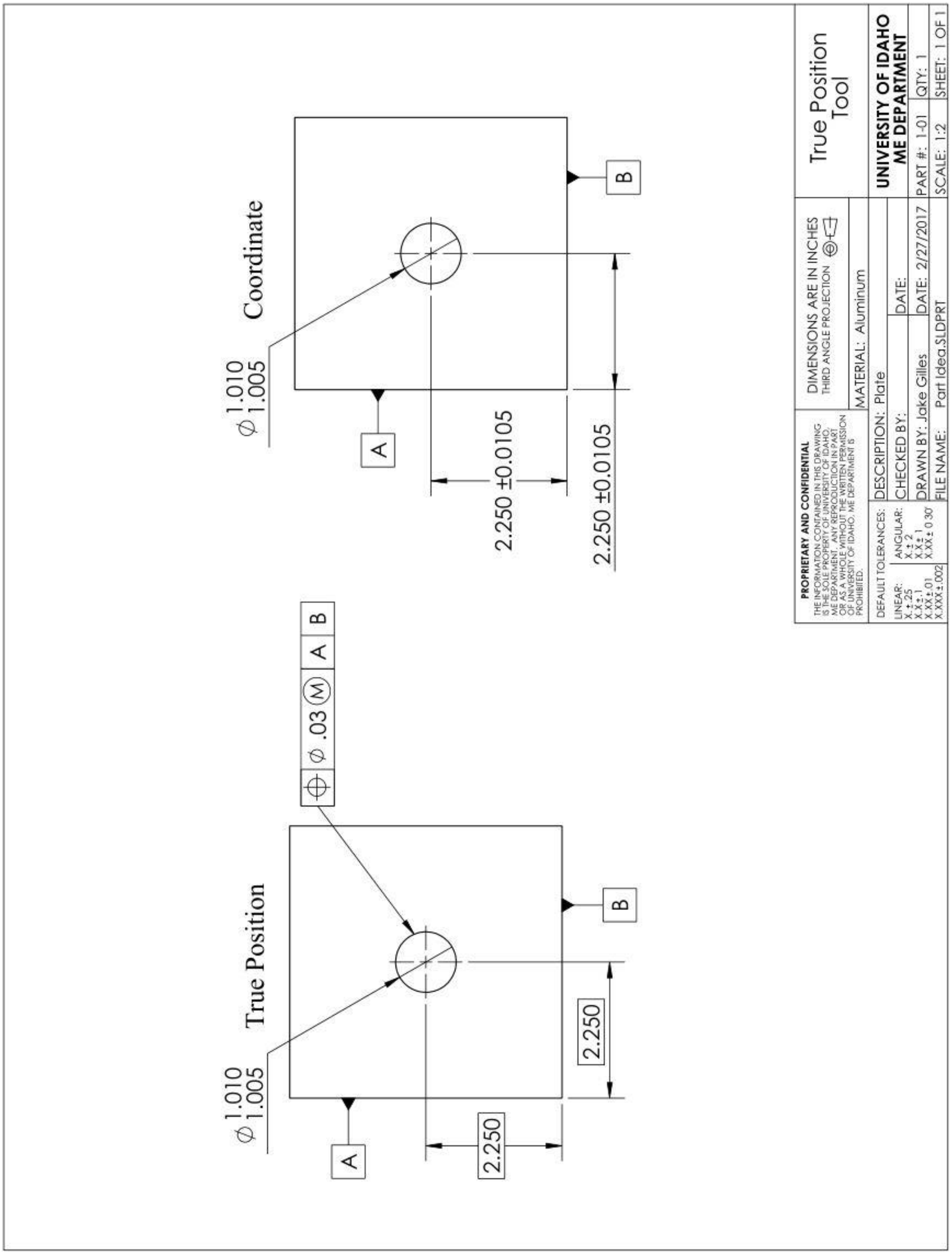
DEFAULT TOLERANCES:
LINEAR:
X. ±.25
X.X ±.1
X.XX ±.01
X.XXX ±.002
ANGULAR:
X. ± 2
X.X ± 1
X.XX ± 0 30'
DESCRIPTION: Top Block
CHECKED BY:
DATE:
DRAWN BY: Jake Gilles
DATE: 3/31/2017
FILE NAME: Top Block.SLDPRT
Break Edges
8.A
8.B
0.625
1.000
Ø 0.506 0.505
Ø .004 Ⓜ A C
1.380 1.370
0.313 x3
Ø 0.258 0.254 x2 Through
Ø .002 A B
Ø .52 X 82°
Ø 0.131 0.130 ↧ .27 Min
Far Side
Ø .002 Ⓜ A B
Ø .44 ↧ .25
1.755 1.745
1.249 1.245
0.749 0.747
0.500
1.000
1.500
2.005 1.995
A
B
C

# Appendix G: Wooden True Position Tool Drawing



# Appendix H: True Position Reference Sheet

## True Position Basics

- Basic Dimension
  - Contains no tolerances
  - Specifies ideal location
  - Called out with the number boxed
    - 

- Maximum Material Condition
  - The dimension at the edge of the tolerance range which leaves the part with the most material or volume.
  - Holes at their smallest allowable diameter or pins at their largest diameter
  - Called out with MMC or Ⓜ
- Datum
  - References edge for dimensions
  - Called out with boxed letter linked to edge 

  - Best placed on mating surfaces
- True Position
  - Acceptable area for location of parts
  - Typically used for round features that mate with other parts
  - Called out with bulls eye ⌖ and diameter ⌀ symbols
  - Commonly uses MMC
  - Must reference at least one datum
  - Acceptable area is increased if the feature is between MMC and LMC
  - Example:

| | | | |
|---|---|---|---|
| ⌖ | ⌀ 0.030 | A | B |

- Mating Parts
  - Fixed Fasteners
    - Dowel Pins, Threaded Holes, Etc.
    - Diameter Positional Tolerance = (MMC Hole – MMC Pin)/2
  - Floating Fasteners
    - Bolts and nuts
    - Diameter Positional Tolerance = (MMC Hole – MMC Pin)
- Total Indicated Runout
  - The greatest range of movement recorded with a dial indicator along a feature when it is rotated about the datum or reference line.
  - Commonly abbreviated TIR
  - Called out with two connected arrows ⌰
  - Must reference a rotational datum surface
  - Example:

| | | |
|---|---|---|
| ⌰ | 0.030 | A |

## Appendix I: True Position Worksheet

# True Position Block Project Worksheet

The next few questions focus on correctly specifying the location of the holes (7.A and 8.A) that the pin fits through.

1. What is the smallest diameter that hole 7.A can be while remaining in tolerance?

    ______________________________________________

2. What is the largest diameter that hole 7.A can be while remaining in tolerance?

    ______________________________________________

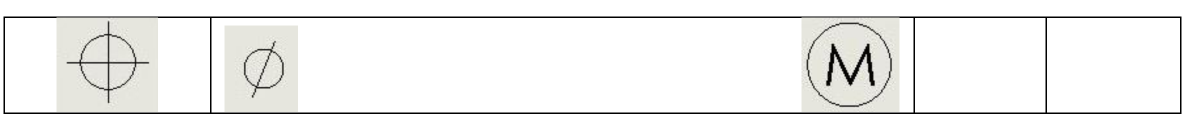
3. What is the maximum material condition for hole 7.A? ________________

    Least material condition? __________________

4. What is the maximum material condition for the lathe pin diameter? ______________

5. Label each of the symbols shown in the true position callout show below.


6. Specify the tolerance of position for holes 7.A and 8.A. Recall that the MMC of the lathe pin is .501”, MMC of the holes are .505”, and the reference datums are A&C.



7. Would the callout, [⌖ | ⌀ .003 Ⓜ | A | B], work for the locating pin hole (7.B) and corresponding hole (8.B) on the top block? MMC of dowel pin is .1255" and MMC of hole is .1295". Explain your reasoning.

8. Given the following measured dimensions for hole 7.B, would the bottom block be accepted or rejected using the tolerance on the drawing? Explain your reasoning.

| Center distance to edge A | Center distance to edge B | Diameter of Hole |
|---|---|---|
| .9990" | .3135" | .1250" |

9. What benefits do you see with this dimensioning scheme over a coordinate dimensioning scheme?

# Appendix J: Total Indicated Runout Worksheet

## Runout Block Project Worksheet

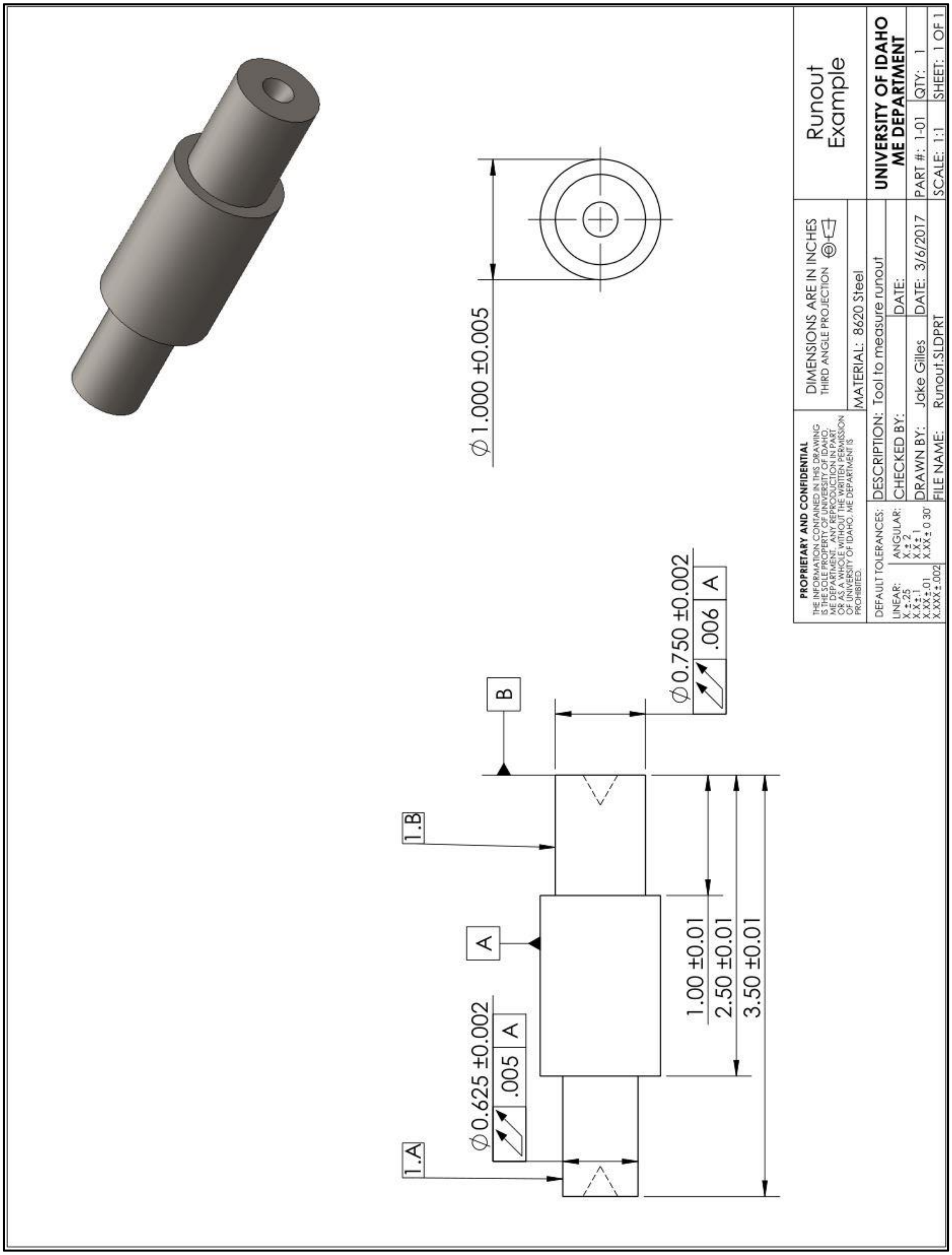
1. Using the supplied drawing on the last page, measure features 1.A and 1.B and confirm if they will be accepted or not. Explain your reasoning.

| 1:A = | 1:B = |
|---|---|

2. What types of parts or assemblies require low or minimized runout?

3. What practices can be used to avoid runout when making parts in the shop? What tools might you use to do this?

# Appendix K: Runout Test Part Drawing



# Appendix L: Boeing Training Manual Theory Pages (Boeing Company, The, 1965)

## True Position Theory

Although only one hole was enlarged on the previous example for illustration purposes, the same principles apply to all holes in the true position pattern.

This example further clarifies the explanation of the true position theory by enlarging two of the holes on the same part as the previous example to illustrate the actual effect of feature size variation on the positional location of the features.

Figure 1 shows the two .247/.253 diameter holes at MMC size (or the low limit of their size tolerance) of .247 and with their centers perfectly in the center of the .007 diameter true position tolerance zone. The mating part situation represented by a functional or fixed pin is simulated. The gage pins are shown undersize an amount equal to the positional tolerance of .007 down to .240 diameter, and which represents the maximum permissible offset of the holes within their stated positional tolerance when at MMC hole size of .247.

Figure 2 shows the two .247 MMC holes offset in opposite directions to the maximum permissible limits of the .007 true position tolerance zone. Note that the worst condition is represented with the edges of the holes now tangent with the diameters of the simulated mating part or gage pins. The holes are within tolerance, and as is seen would satisfactorily pass the simulated mating part condition as represented by the gage pins.

In Figure 3 the .247/.253 diameter holes have been produced to the opposite, or high limit (or minimum material condition), size of .253. It can now be seen that when retaining the same offset and tangency situation between the holes and mating part of gage pins as in Figure 2 above, the produced center of the holes have been allowed to shift beyond the original .007 tolerance zone to a resulting .013 diameter tolerance zone and yet still provide an acceptable situation.

This illustrates the inter-relationship and affect of size and position tolerances upon one another which is utilized in true position dimensioning and tolerancing.

Although in this example we have used only two holes and have offset them in opposite horizontal directions, the same reasoning applies to all the holes in the pattern; and, as well, each individual hole could be offset within its tolerance zone in any direction around 360° and provide an acceptable situation.

It should be noted that a functional or fixed pin gage such as is used here to explain the true position theory can be used only to check the positional location of the holes. As is illustrated, added positional tolerance can be added as the holes increase in size or depart from MMC size within their size tolerance range. Hole size tolerance, however, must be held within the specified tolerances on the drawing and must be checked individually and separately from the positional check.

The "diameter" or round tolerance zone callout has been used in this illustration and in all others in this booklet. It should be clarified, however, that the "radius" callout may also be used. The method used should be indicated by the terms "DIA" or "R".

See GENERAL RULES section - "Shape of Tolerance Zone for Positional or Form Tolerances".

# True Position Theory

For the purposes of explanation of True Position we should review the True Position Theory.

In this illustration a comparison is made between a part dimensioned and toleranced using a coordinate system in the upper picture and the same part dimensioned using true position in the lower picture.

The first thing noted is that the tolerance zones for the hole centers are square in the coordinate system and round in the true position system. True Position tolerance zones on round holes are always round.

The next thing noted is that the hole center location tolerance in the upper example is a part of the coordinates (the 2.000 and the 1.750 dimensions). In the lower example, however, the tolerance is a part of the hole size dimension shown in the feature control symbol box at the right. This is an indication of at least one objective here to tie in each hole location by a positional relationship to an individual location rather than reference off another hole and thereby accumulate its error.

We note also that we have permitted a .007 tolerance zone in the lower true position example and only .005 in the coordinate example.

For clarification of this point we will pick up one of the tolerance zones and enlarge it showing the .005 square zone and the calculated 45° diagonal of .007.

The black dots represent some inspected centers of this hole. Some fall in the zone and are acceptable. Others are outside the zone and would be rejected by an inspector.

We now superimpose the .007 round true position tolerance zone on the example and see that more of the locations are now acceptable. At this point we can reasonably question the validity of checking the accuracy of a round hole with the square tolerance zone. Note that the locations represented by the dot on the diagonal in the upper left and the dot on the center line to the left are about the same distance from the center yet one is acceptable and the other would be rejected under the square zone system.

The .007 acceptable tolerance zone is of course calculated at MMC or the smallest hole size. As the hole sizes get larger in actual production it can be readily seen that this increased size affects the position because more shift in center position is now possible. This adds more to the total possible tolerance and brings it up to .013 diameter. By true position use we have increased the manufacturing tolerances from .005 to anywhere between .007 and .013; or, anywhere from about 40% to 160%. We have also assured assembly of the parts and vastly simplified inspection techniques.

It should be noted here that the True Position tolerance zone applies to the entire depth of the hole.

# *Runout ↗

Definition:

Runout is the deviation from perfect form of a manufactured part surface normally detected by full rotation of the part on a common axis when using a dial indicator (or equivalent measuring device).

Runout Tolerance:

A runout tolerance establishes a means of controlling the functional relationship of two or more features of a part within the allowable errors of concentricity, perpendicularity and alignment of the features. It also takes into account variations in roundness, straightness, flatness, angularity, and parallelism of individual surfaces. In essence, it establishes composite form control of those features of a part having a single common axis or multiple common axis. Necessarily then, measurements should be taken under a single setup.

In RUNOUT tolerancing a datum axis must be established to be used to relate the various features concerned. This axis may be established by a diameter of considerable length, two diameters having considerable axial separation, or a diameter and a face which is at right angles to it. Insofar as possible, surfaces used as datums for establishing axes should be functional.

In extreme cases the pitch diameter of a thread, gear or spline, or some other feature, may be desirable for establishing an axis but the use of such features as datums should be avoided. A nearby surface, even though non-functional, may be used to better advantage.

Features which have no functional relation to the common control axis or where it may be necessary to control the individual surfaces more accurately than the runout tolerance, may be controlled by separate symbols or local notes relating the surfaces directly to one another.

The runout tolerance when the part is mounted on a common datum axis (e.g., X-Y) means that all designated surfaces on this common axis (including the mounting surfaces if a limit is designated must be INDIVIDUALLY within the full indicator reading specified when so mounted.

Any two surfaces on a common axis which are individually within their specified full indicator reading (runout tolerance), are related to each other within the sum of the indicator readings.

* Not per MIL-STD-8C. If used under military contract must be defined or explained on drawing.