Tolerances Considerations in 3D printing

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ABSTRACT

A seven-part of a belt roller support assembly system shown Figure 1 is a student project to sophomore engineering Computer Aided Design class. The objective of this project was to apply our basic understanding of 3D printing and tolerances in order to minimize error in prints and increase repeatability of prints. The knowledge gained from this project would apply to the various courses at Frostburg State University that implement 3D printing as a part of the curriculum.
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1. Introduction

The objective of this project was to work in a team to apply the skills learned in CAD to create a 3D printed object for a Belt Roller System. Our group decided to take one of the earlier homework assignments and create a working model. [1]

When using additive manufacturing, the quality of the created object depends on the specific device used. The additive manufacturing laboratory at Frostburg State University utilizes three different 3D printers. These include the Catalyst Dimensions Printer, the MakerBot Z18 Printer, and the MakerBot Replicator Mini Printer. All three of these printers are considered fused deposition modeling (FDM) machines. This means that they each have a spool of a solid, plastic filament, which is then heated past its melting point and extruded through a nozzle to create a layer of the object being printed. Once the filament has been extruded, it then solidifies again after a brief period of time. When printing on the Catalyst Dimensions Printer, the dimensions of the printed object are virtually identical to those in the CAD program, with statistically negligible error. However, the MakerBot Z18 was used for this project. Although the MakerBot Z18 creates objects with dimensions that are very close to those specified in the CAD program, there is a small amount of error. When printing a single object that will not be fixed to anything else, the error is negligible. However, when printing things to fit on, in or around something else, the error can cause problems. Depending on the intended use of the parts, this error can easily compromise the functionality of the parts.

2. Reasons for the Differences in Tolerance

This difference in tolerance can be attributed to a number of factors. First, the Catalyst Dimensions Printer cost tens of thousands of dollars, while the MakerBot Z18 cost a couple thousand dollars, and the MakerBot Replicator Mini Printer cost a few hundred dollars. Part of the difference in prices comes from the size of the printer. The Catalyst Dimensions Printer has the largest build plate, with the MakerBot Replicator Mini Printer having the smallest build plate. Naturally, as the size of the printer increases, so will the price.
However, the most significant reason for the difference in price is the quality of the machine. The Catalyst Dimensions Printer was designed to have a very small tolerance while the MakerBot printers were not.

The Catalyst Dimensions Printer also has a heated build chamber that prevents parts from warping as the material cools. The build chamber is well insulated, and the door to the build chamber creates a seal between the chamber and the outside environment when it is closed. The chamber is kept at a temperature below the melting point of the filament so as to allow the filament to solidify, but it is high enough that there is not a drastic temperature change from the extruder to the part. This consistency in temperature allows the material to cool slowly, which prevents warping. The MakerBot printers however, do not have effectively heated build chambers. The MakerBot Replicator Mini Printer does not have a top cover, and the thin plastic walls that make up the sides of the printer have slits in them. This lack of insulation means that the part is not protected as it is being printed, and the quality of the print can be drastically affected depending on the conditions of the environment the printer is in. The MakerBot Z18 Printer does have the capability to heat the build chamber. However, the chamber is not properly insulated at all. While the printer does have a top cover, it has a number of holes designed in which allow heat to escape. The walls of this printer are glass, so they help keep heat in better than thin plastic, but again, the door to the build chamber does not create a seal between the chamber and the outside environment. When the settings have adjusted to heat the chamber, the printer oftentimes will be unable to print because the chamber cannot reach the temperature it is set to. This problem occurs whenever the temperature is set above room temperature, which it needs to be in order to be effective considering the filament is extruded at 215ºC. This drastic change in temperature from the extruder to the build plate itself cools the material quickly. If the part is small enough, there is not much noticeable warping. This is most likely because as the material begins to cool, it then receives another layer of filament on top of it, raising its temperature and slowing the cooling process. However, with larger parts, there is more time between when a specific point of the part receives a second layer, meaning the layers have more time to cool. This warping can lead to drastic differences between the actual printed part and the CAD file, which may be a reason why the tolerance is much bigger on the MakerBot Z18 Printer.

Another possible factor that could affect the tolerance is the material the part is printed in. The Catalyst Dimensions Printer uses ABS plastic as model material and a soluble support material, while the MakerBot Z18 Printer uses PLA for both model and support material. ABS is a much higher quality material than PLA, so it is more reliable.

3. How Tolerance Applies to our Project

All fifteen components of the belt roller system interact closely with other components in the design. Therefore, it was critical that we allow sufficient tolerance for the whole design. We established a set of guidelines to dimension a part to print. It was observed that if an object with a hole was printed with exact intended dimensions, the hole on the printed object was too small for the intended use. Similarly, a part printed with an intended outer dimension was too large once actually printed. By tracking these errors and taking measurements using digital calipers, we observed consistent error in printed parts- outer dimensions were being printed larger than intended, and inner dimensions were being printed smaller than intended. The position of every edge was shifted by consistent amounts depending what region of the object the edge was on. By comparing measurements, it was clear that each edge was being printed about 0.01 inches above or below the intended dimension value. This was especially apparent on round parts or parts with holes, because the diameter was consistently increased or decreased by 0.02 inches, or the radius by 0.01 inches. Once making this observation, we tested our theory.

In order to determine a solution for the tolerance issue, we created a test part. We designed an axle into which a small metal pin could be inserted. We knew the diameter of the pin, so we simply added 0.01 inches to the radius of the hole in the axle before printing. Once the print was complete, the pin was inserted into the axle. The pin fit perfectly, contacting the inside of the axle in every direction. Now, we know how to create objects with physically accurate dimensions.

This rule of thumb (0.01 inches per edge) can be used to allow objects to fit in or around one another, but the tolerance issue is still not solved. Although the pin fit into the axle very well, it was not tight, and could slide or become loose without much force. In order to fix this, we simply reprinted the axle with half of the tolerance (0.005 inches) added to the desired radius value. This resulted in an axle into which the pin could fit, but required more force to fit, and did not come back out easily.
This was our desired outcome for this project because while we wanted all of the parts to fit together, we did not want them to be able to move much. We wanted all of our rotating parts to rotate together and the support pieces to be held steady to keep the part intact.

At this point, we have established a rule of thumb for adjusting dimensions in CAD so that the printed object fits flush with another object, and another rule for a printed object to fit tight with another object. In the belt roller design, this is vital for the interaction between the shaft and the collars, the collars and the wheel, and the supports, washers, screws and the plate with one another. However, neither the fit nor the tight tolerance would suffice for the interaction between the shaft and the supports. The shaft is intended to roll within the top holes of the supports. Obviously, this would not happen using tight tolerance, and it would not move well with the fit tolerance as it would create too much friction. Therefore, we needed a third tolerance value to allow movement between objects. Since we already created an axle into which a pin could be placed, we then created a simple wheel to be mounted on the axle using the pin. Since half of the fit tolerance resulted in a tight fit, we tested one and a half times the fit tolerance (0.015 inches per edge in a single direction) to allow something to move. Based on this idea, we adjusted the inner radius of the wheel by adding 0.015 inches to the intended radius. This resulted in a very small gap when the pin was inserted into the wheel, with just enough space for the wheel to spin about the pin. Now, we have established tolerances for tight, fit, and loose connections between a printed object and an object with known dimensions.

Adjusting the part dimensions for the test axle was fairly simple, as it only involved dimensions in one direction since the important dimensions were in the same plane and symmetric, and it was for a printed object to fit around a physical object. However, it is much more difficult to correctly adjust the dimensions for the belt roller system, as it involves many more interactions between parts in every direction. Moreover, the interactions of components of the belt roller system are between printed parts with one another, not a printed part with a physical object that has known dimensions. But by addressing the tolerance systematically, we could treat certain dimensions as if they are on physical objects, and adjust the dimension of the object in contact accordingly. For example, we now know that if we print a cylinder with diameter equal to 0.98 inches, the actual printed object will have a 1-inch diameter. Therefore, by adjusting certain dimensions using the fit tolerance in the CAD program, we could treat them as physical objects and adjust other dimensions around them.

To adjust the dimension, one must simply adjust one dimension to the fit tolerance, and the dimension on another object that will be in contact with that surface can be adjusted according to the intended tolerance (loose, fit, or tight). Below is a table showing the original values and the adjusted values of every dimension that was altered before printing (all in inches).

Table 1. Original values and adjusted values of every dimension that was altered before printing.

Part Name	Dimension All in inches	Original Value	Adjusted Value	Intended Fit
Wheel	Inner/dia.	0.984	0.1004	Fit
Collar	Outer/dis.	0.984	0.974	Tight
Collar	Inner/dia.	0.787	0.807	Fit
Shaft	Outer/dia.#1	0.787	0.777	Tight
Shaft	outer/dia.#2	0.472	0.452	Fit
Shaft	Inner/length	3.307	3.277	Loose
Shaft	Total/length	4.724	4.704	Fit
Support	upper hole Dia.	0.472	0.502	Loose
Support	lower hole Dia.	0.413	0.433	Fit
Support	Length	1.57	1.55	Fit
Plate	Inner length	3.701	3.681	Fit
Plate	Total length	6.929	6.949	Fit
Plate	Hole	0.413	0.433	Fit
Washer	Inner Dia.	0.433	0.433	Fit
Bolt	Diam.	0.394	0.403	Tight

4. PRINTING

Now that the dimensions have been adjusted, the parts can be printed. Components on the bottom of the assembly contacting the build plate were oriented vertically so that the top side that would be visible once assembled would not be degraded due to support material. The cylindrical components intended to move were oriented with the circular shape facing upright. In this orientation, the layers of material would be in the same direction that the object would spin, allowing for less friction and smoother movement once assembled. Finally, the settings were adjusted to standard quality, 10% fill, and breakaway support. The print was about 22 hours long, but required minimal material since it was printed with 10% fill.

5. COMPARING THE SOFTWARE

Throughout the course of ENME272, we learned how to use three different types of software including Autodesk Inventor, Creo Parametric, and SolidWorks to create CAD files, including part files, assemblies, and drawings. In order to bring a part to life, it must be exported as a .stl file so that it can be loaded into the 3D printer. All three types of software have the capability to create .stl files, so we had to choose which software to use for this project.

Inventor

Pros

- Very user friendly
- Provides description and sample video demonstrating how to use a tool
- Both group members have had prior experiences working with this software
- Very easy to create section views in

Cons

- Can crash unexpectedly
- Creating a threaded part is difficult because the threading tool only creates an image of what the threading would look like, but does not actually create a feature

Creo

Pros

- Has good parts analysis software
- Requires less computing power to run, therefore decreasing the chance of crashing

Cons

- Must create a work plane in the part before creating a section view drawing
- Extremely difficult to modify sketches or features without deleting them
- Cannot change orientation of the part (front of the part must be drawn on the "front" plane)

SolidWorks

Pros

- Fairly user friendly
- Easy to make animations of exploded views
- Has extensive tutorials from beginner to advanced ability

Cons

- Difficult to change view orientation while drawing part

- SolidWorks PDM has a tendency to crash, and close any other open programs with it.

As mentioned previously, these parts came from a homework assignment, so we already had experience drawing them. We had drawn the exact same parts in Creo and Inventor, and we had drawn similar parts in SolidWorks. With all of the pros and cons considered, we ultimately decided to use Inventor to create modifications to the parts.

6. POTENTIAL USES FOR THE PROJECT

The assembly of these parts was first presented in the homework as a belt roller system. In real life, this type of system could be used for a mounting bracket for spooled material, as a roller without anything on it (perhaps underneath of a sliding surface), or simply in the manner described by its name, a roller for a driven belt system. However, because we created a scaled version, and it is made of PLA, a material that is not very durable, it is highly unlikely that our project will be used for this purpose. However, we do intend to use the project as a sample model for future ENME272 classes. For most students taking the class, they have never worked with CAD software before, or have had very little exposure to it, so it can be difficult for them to picture how what they are drawing on the computer can be brought to life. Hopefully if given a physical model of what they are drawing, future students will have an easier time visualizing how to create their parts and the purpose of them. Seeing a working modeling of what they are drawing can also help them realize how important CAD is in the design process. We chose to print all of the parts as they were drawn for the homework, individually, instead of all together in the assembly for multiple reasons. First, because we do intend for this project to help future students, it would be more beneficial to them to be able to take the model apart and inspect each part individually than guessing what they would look like. Second, printing the parts to fit together really allowed us to learn about the tolerances of the machine, which can be used for future applications. This is knowledge we would not have gained by printing the assembly as a whole.

7. CONCLUSION

Modifying the part files so that the printed parts would all fit together as intended helped us learn a lot about the printer and how it works. This was a perfect project to use to test tolerances because it involves multiple different types of connections including loose, fit, and tight. We hope to apply this knowledge to future projects with moving parts to maximize the efficiency of our printers. Typically for moving parts, we use the Catalyst Dimensions Printer because it is so reliable, but this proves to be more expensive than using the MakerBot machines because ABS is five times more expensive than PLA. Because we can now use PLA to print moving parts, we can greatly reduce the costs of projects.

In gathering data about the tolerances, we gained valuable experience with experimenting with dimensions and designs. We learned more about why certain standard tolerances are the way that they are, and how different factors can affect the tolerances. We were able to take information about standard tolerances and apply it to our printer and design.

REFERENCES

[1] Zhang, Guangming, *Engineering Design and Cero Parametric 4.0*, College House Enterprises, LLC, 2017.

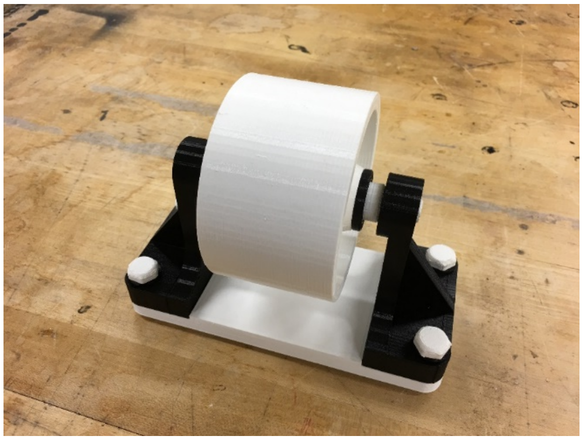

Figure 1. Belt-Roller-Support system by 3D printing.