Calibrating for Angularity Error and Improved Bed Flatness

After ultimately rebuilding my delta printer with a MAX METAL frame and Trick Trucks purchased from Trick Laser, I had significantly reduced printed part dimensional error but was left with a nagging angularity error that was more evident on larger parts. I spent a fair amount of time qualifying the frame and was able to confirm the towers were square within 0.1° and equilateral within 0.0025". The arms were verified to be equal in length which left the effector and the u-joint carriage as the next possible sources of error. When I originally built the machine I had to file and fit the u-joints. I suspect that despite my "careful" approach, I ultimately introduce some inaccuracies during the u-joint fitting process..

My search for an easy to implement firmware solution and calibration for the next step of improved part accuracy led me to a means of simple mechanical adjustment.

Error Mapping / Calibration

If you have witnessed the processes used to error map a CNC or CMM using a known ball bar or laser measurement system, they ultimately depend on having some sort of calibrated standard to measure against.

The current state of automatic bed leveling and calibration processes can dramatically improve visual printed print quality, but there is no guarantee of accurate part angles and sizes. They use the bed as a 2D planar reference which is not sufficient to compensate for 3D dimensional errors in the machine.

My goal is to reduce as much of the mechanical error in the machine as possible and then let the automatic calibration tools perform the fine tuning to help with first layer adhesion and part appearance.

These Instructions are based on a method presented by Taede de Jong (http://www.thingiverse.com/thing:745523). I recommend taking the time to read the process he describes which makes it easy to understand a manual approach of error compensating for machine build inaccuracies. He details how to make firmware modifications to fine tune the calibration. Repetier and Smoothie currently allow for error mapping some of these parameters within the configuration without modifying the code.

I will be focusing primarily on addressing the observed angularity error without use of firmware changes by minimizing physical geometry error within the printer.

Process

The process of checking and adjusting is iterative. I recommend focussing on one tower at a time to avoid too many changes which can make validation of improvement difficult. My experience was it took 4 total print cycles.

- 1st was a base line print
- 2nd was to adjust the X tower
- 3rd was to validate a 2nd adjustment to the X tower (this was then used for the Y tower)
- 4th was to validate an adjustment to the Y tower.

If you have a means of directly measuring the angularity error of the calibration object and doing a bit of trig work, it's possible to minimize the iterations.

Print time is approximately 1 hour for the calibration piece and about 7.8m of ⌀1.73mm filament.

Tools

- A good quality 30/60 drafting triangle. I prefer a transparent triangle as it makes checking with a light source easier for me. If you want to check for tower parallelism, get two triangles. The 2nd drafting triangle can be a 45.

Assumptions

- The printer towers are square and equidistance within reasonable use of hand tools. **See the later part of this guide for a suggested technique.**
- Arm lengths should be as equidistant as possible.
- The printer is calibrated well in regards to delta arm length, horizontal radius, end stop, etc.
- You are not printing with any other type of error correction in play to skew the results.
- The heated bed has had plenty of time to stabilize prior to printing to minimize dimensional errors after cooling.

Calibration Part Print Instructions

- Use an easy to print material with minimal warping such as PLA.
- Avoid overfilling the part. If the top layers are not flat, it can make inspection more difficult.
- Print at 0.1 or 0.2mm layer height. (I used 0.2mm for the first layer and 0.1mm for the other layers). The calibration guide was designed with 0.2mm layers heights.
- Print exterior perimeters first for best accuracy.
- 1st layer smash will not impact the accuracy of the process.
- The printer needs to be tuned well enough to minimize blobs on perimeter surfaces. The calibration object is designed to tolerate blobs and errors on interior corners.
- I used 30% infill. Print to suit, but I would avoid use 100% infill.

Iteration Process

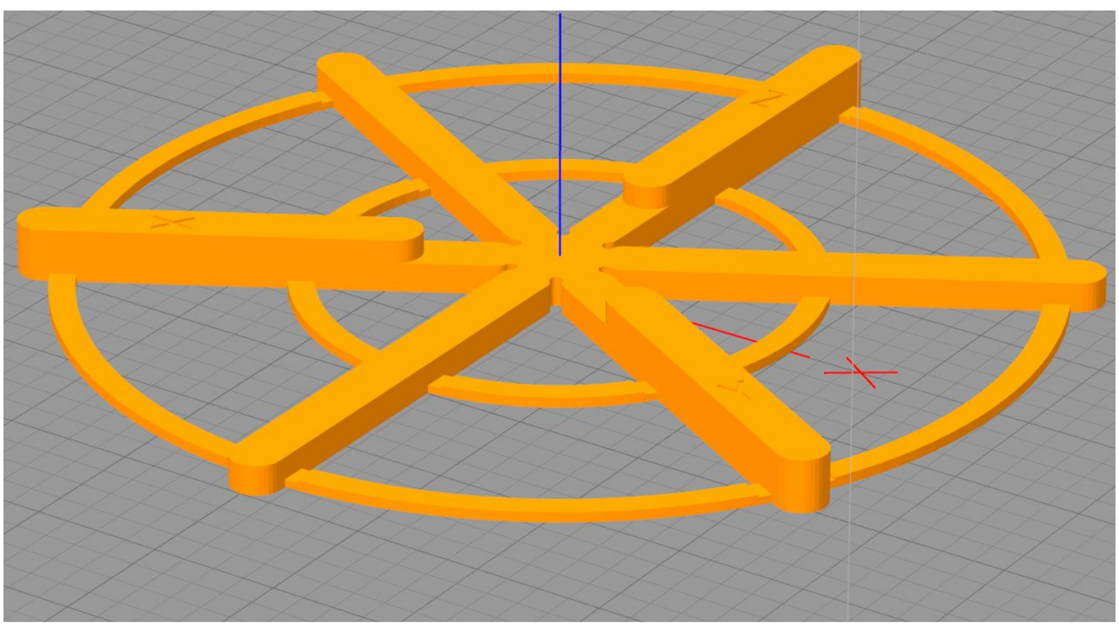
- Print the calibration object and cleanup any blobs and strings as needed.
- Verify angles with the 60° triangle. After inspection of all angles, make a determination as to which tower will be left as a fixed reference. Jong's approach uses the Z tower as the fixed reference. But close examination may identify one tower as being preferred.
- Shift the arms within the u-joint carriage as need.

    - Example: If the angle between the X and Z tower is too large, then you need to shift the arms to create a clockwise rotation effectively reducing the physical angle between the towers.
- Iterate as needed.
- Focus on fixing angularity error before you consider length and width measurement errors.
- If you end up making a significant enough adjustment in angularity, it is possible you may need to reset the tower endstops between iterations. Tower zero heights do affect each other.

The Calibration Object that I have supplied has the following features.

- It can be checked with a quality drafting triangle. I don't trust printed paper unless it's a calibrated mylar print. *(Old school optical comparator overlay for the "experienced")*
- Inside corners are relieved to prevent influence of blobs and corner radii that are a resultant of nozzle diameter and less than perfect print calibration.
- The part is tall enough that the top layer is higher than a typical drafting triangle to avoid risk of influence.
- The 3rd significant step in the part (with Tower indicators), gives you easy to measure geometry for size accuracy checks. (60mm x 8mm)
- The extra height lets you focus on angularity first before having to deal with bed level. Bed level should naturally improve as angularity improves.

Sample Images



Calibration Object

Sample check of the 60° angle.

U-Joint Carriage Adjustment

Use of the Trick Laser Arms made adjustment easier, but it is possible without by placing shim washers on the axle between the u-joint and arm. I made adjustment room possible, by filling a bit of plastic off one side to allow a lateral shift. No matter the approach used, you want to ensure spacing between all arms are equidistance at all times. If using the stock aluminum or plastic u-joints, you can start with paper as a shim as a test and eventually replace with a more durable solution (McMaster sell sheets of PTFE shim stock).

In this photo, you can see a gap in between the brass washer on the u-joint carriage and nut on the right while the washer and nut are tight on the left side. When I checked the X tower relative to the Z, I had an result angle that was about 61°. I removed a small amount of material off the left side of the u-carriage to allow room to shift it to the right. This small shift corrected the angularity error.

Note:

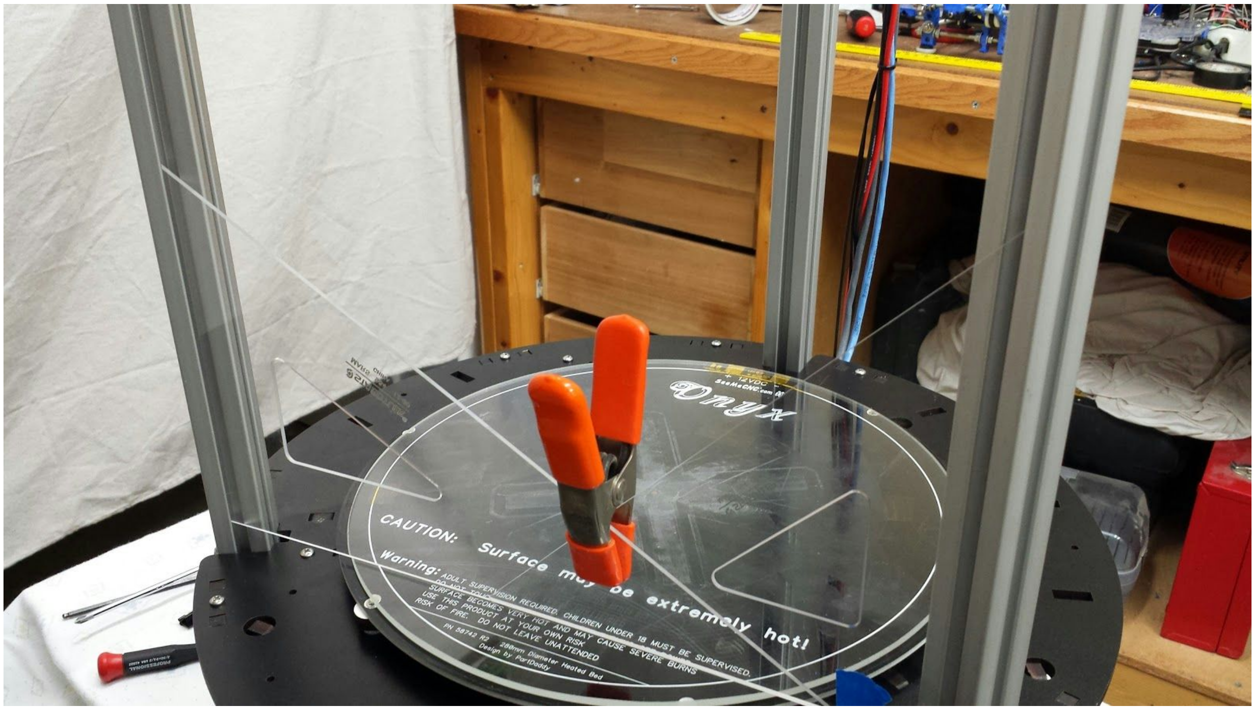
Theoretically, it is possible to apply compensation to the effector instead of the u-joint carriage. I chose the u-joint carriage because I originally removed the most material from them when building the printer and assumed that this is where I introduced the most error.

Checking for Square and Tower Parallelism

Below is the method I use to check the machine for square and tower parallelism. I'm not fond of using framing squares. They tend to be stamped and inaccurate unless you've tweaked it or spent the money for a good one, and they can break glass if dropped.

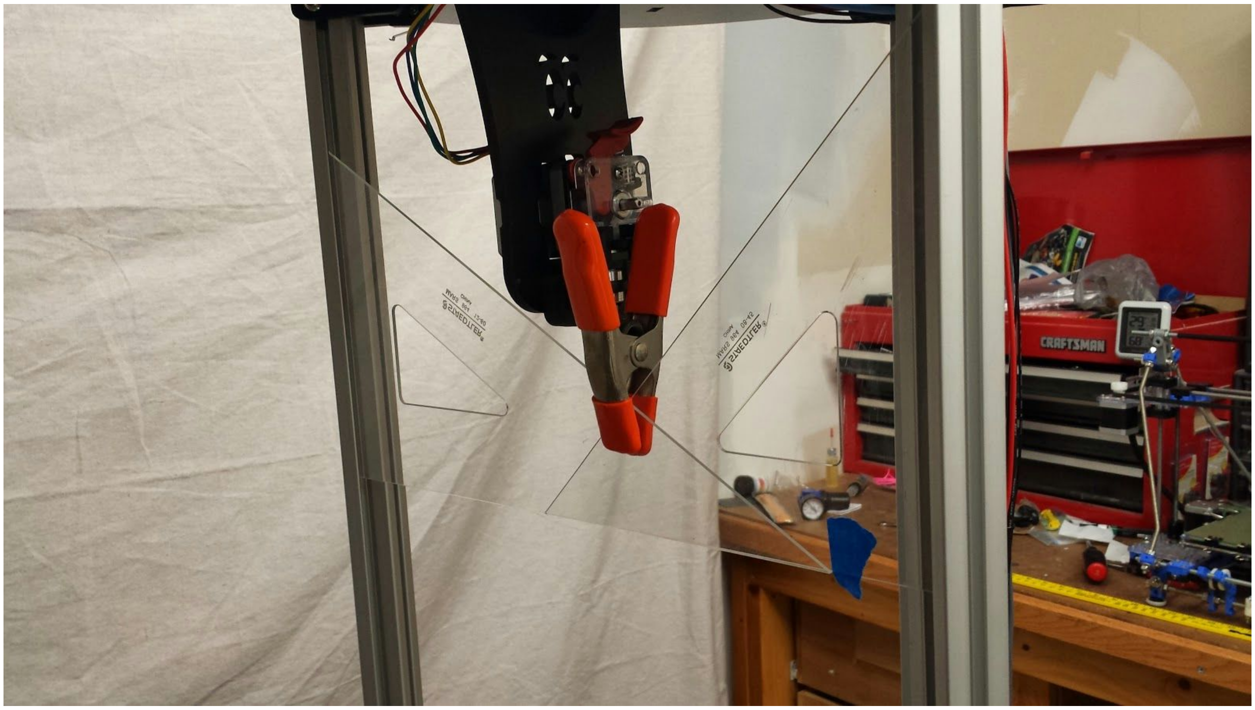
I always perform a final check against the bed with the glass plate installed. It's alway a very good to check for square without the bed during the build of the machine to check frame geometry, but the bed needs to be square also.

When you tuck the triangle into the slot and rotate it at an angle, it removes all the play and forces it to square up on the extrusion nicely. This creates a repeatable process that avoids having to deal with the slight angle that exists on the exterior faces of the extrusion.



The spring clamp was used for photography purposes only.

If you squeeze the triangle against the extrusion (grip between the interior cutout of the triangle and the outside face of the extrusion and slide it to down the glass plate, you can easily check for square. Use of two triangle on opposite towers can show that both are square and parallel to each other. If one triangle is square to the bed and the other is not, you've got some assembly errors to sort out.



If you slide the triangles up to the top, mark the tip where one triangle overlaps the next and check for the same distance (mark) at the heated bed, you can easily identify parallelism error that is not evident at one height. The triangles should also be parallel to each other at their bases.

Next step is to check the distance and parallelism between the other remaining towers to verify they are all equidistant from one another.

If you prefer, a thin point permanent marker can be used to mark a triangle intersection and then use some rubbing alcohol to clean it off later. A buddy can be very helpful at this point.

This method is very repeatable and creates a precise visual method without use of expensive tools. You don’t need indicators, calipers, CMM’s, etc to ensure you have a good foundation to print dimensionally accurate parts.

When building my Rostock Max v1 printer, I tucked all towers tight radially in the slots, and then bumped two of the towers out radially to match the tower with the largest radial distance from center after first checking for equi-distance. I did this with just the base assembly only, and after set, installed the top plate ensuring it did not bias the assembly by sanding on a slot or two. It’s takes a bit of patience, but it is doable.