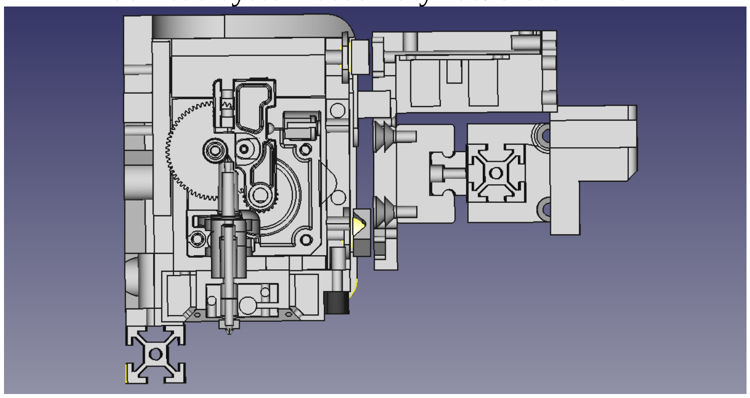
Athena Toolhead System Design Hand Off Document

Toolhead system assembly rev. 3 cut in half



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1.0 Introduction:

The purpose of this document is to lay out the current design status as well as the tasks that will need to be completed in order to bring this toolhead to market. As of June 2017 the toolhead is in the 3rd revision.

2.0: Overview:

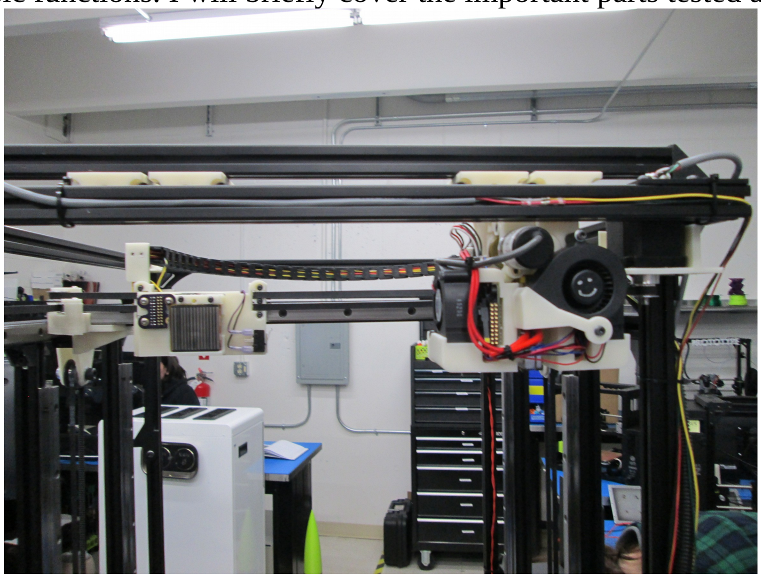
Development goal for the Athena toolhead system is to make a better multi-tool printer. Going over the previous revisions will help with understanding the current state of the toolhead and give direction for the future. Making this an automated modular system seems to be the best path forward. The list below highlights the benefits of such a system.

a) Faster dual printing.
b) Intelligent toolheads.
c) Multiple color printing.
d) Multiple material printing.
e) Higher x and y accuracy with multiple toolheads.
f) Minimal user intervention (automated calibration of multiple toolheads).
g) Variable z adjustment for multiple toolheads.
   - Different size melt zones.

- Mix different brands of toolheads.
- Leaves endless possibilities for development of mix and match tools (3d print toolhead and milling toolhead).

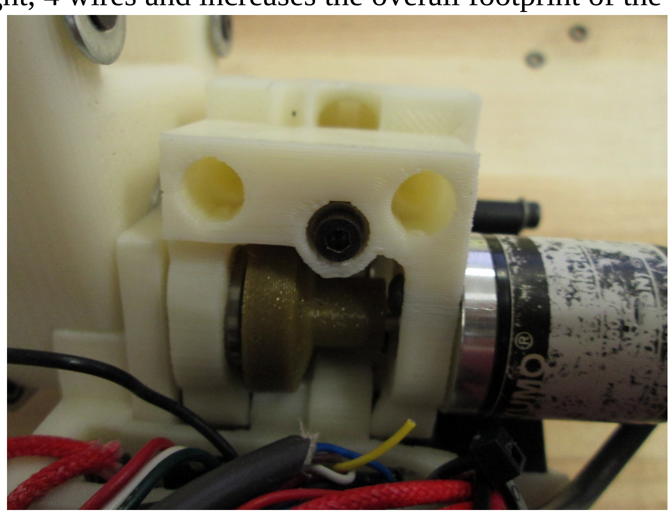
3.0 First working concept

This first prototype involved testing many ideas for the first time. Only one toolhead was made for this revision to test the basic functions. I will briefly cover the important parts tested and results.



Parts test list

a) Encoder as idler.
   - This part was dropped after this revision.
     - Based on our accuracy and size requirements it was difficult to procure an off the self encoder, we only found a couple that might work.
     - Mechanical design was challenging since side loads could damage the encoder.
     - Adds weight, 4 wires and increases the overall footprint of the toolhead.

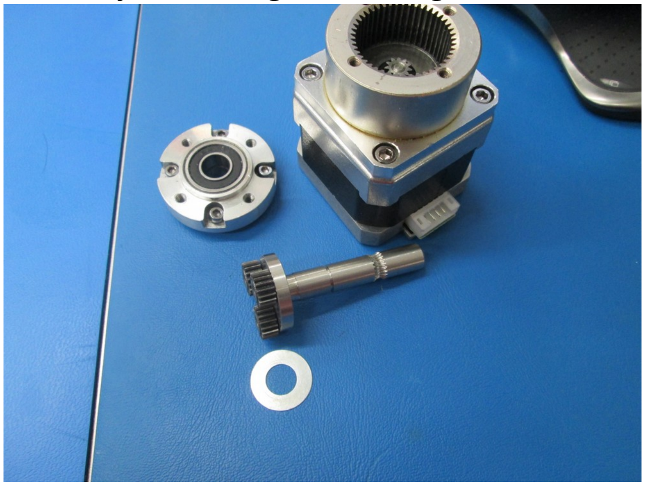


b) New idler tension system to replace Greg wade.

    - This is no longer a requirement since the current rev. is using E3d's idler system on the Titan Aero which works extremely well.

c) Blower fans for heatsink and extruder cooling.
    - Testing a variety of blower fans I came to the conclusion that these will work much better than our existing fans.
        - The fans we use now are "open air fans" they are made to move air in an unconstrained environment which limits the way a fan duct can be designed. The blowers will push the air more efficiently in constrained conditions, allowing more freedom when designing fan shrouds.

d) Planetary gearbox with custom hobbed bolt shaft.
    - This test was considered successful and continued to revision 2, however the Titan Aero replaced this in the current revision since it was better all around solution.
        - No dust from printed gears rubbing.
        - Did not have to worry about the gears wearing over time.



e) Dove tail alignment with magnet holds.
    - The results from this were mixed.
        - Did its job of generally aligning the toolhead into the dock and holding it.
        - Had a significant amount of slop that caused misalignment of pogo pins and inconsistent pick up and drop off of toolhead.

f) EPM (Electrical Permanent Magnet).
    - Was considered a success for many reasons.
        - Strong holding force.
        - Controlled by pwm on Replicape.
        - Repeatability with minimum wear on parts.
        - Gave us the idea to try kinematic coupling with the EPM as the preload.
        - Small magnetic field that doesn't extend beyond point of contact.
        - Mounting of the current EPM is not ideal because the screw locations interfere with the precision rail block.
        - May not be available for mass production off the shelf.

g) Alignment holes for docking.

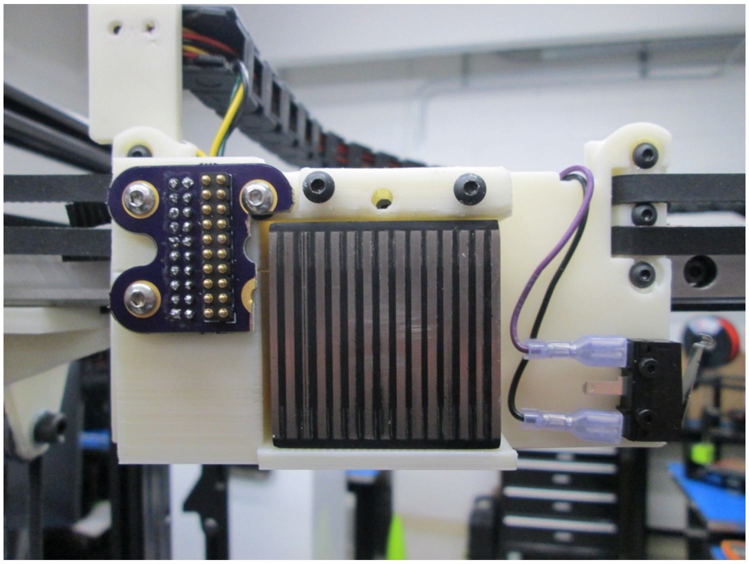
- Using two screws on the x carriage and holes on the toolhead for alignment increased the success rate of docking and undocking.
  - This success led to the development of a kinematic coupling setup in the next revision, that would increase our accuracy and repeatability.

h) Toolhead on board electronics.

- Thermocouple.
  - Was moderately successful; it still has a few issues to resolve.
    - Thermocouple was used instead of thermistor since they are rated for higher temperatures (above 300C). A thermocouple will allow us the option to design a high temperature toolhead in the future.
    - The thermocouple was read at the toolhead board and information was sent via the data lines to main board. Interference on the data line was fairly common. The length of the wires and having high current wires running parallel contributed to the interference. Some changes were made to the board to help combat this in the second rev. but other solutions may need to be explored.
- Encoder.
  - Didn't end up getting tested and was dropped for now.
    - Because of the issues stated in section a) above; the encoder has still not been tested.
    - Have not figured out how the correct way to enable this in the firmware.
- Fans, heater, and motor output.
  - Worked great on first try.
    - Heatsink fan started as 3v output but since 3v fans are uncommon it was changed to 5v in second rev.
    - Extruder fans and motor still run on 24v.
- Pogo pin contacts.
  - Testing was successful.
    - These require fairly tight tolerances for the pins to align correctly. The first rev. had a large tolerance stack up and slop in the dock so the pins would occasionally misalign and short frying the electronics.
    - The pins can accidently be soldered on at an angle, an acceptable tolerance should be given to ensure this does not happen.
    - Pogo pins were chosen because they are rated to reliably work even after millions of cycles.

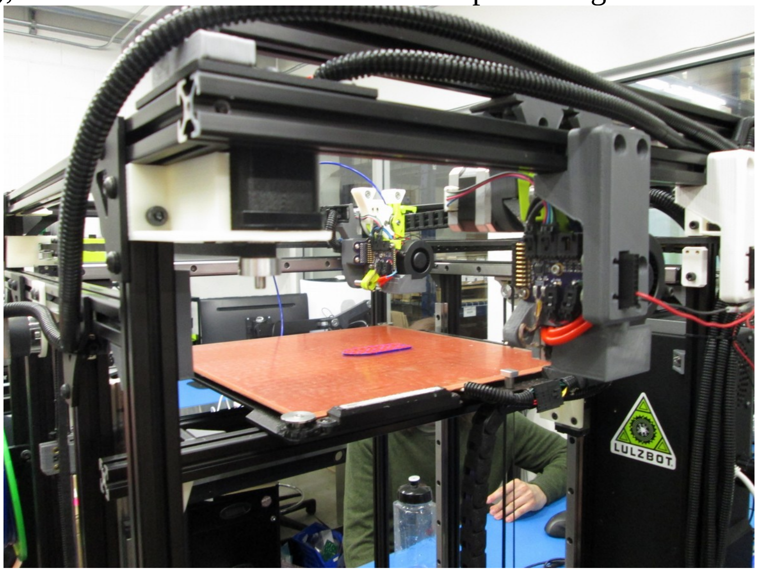
i) X axis and docking board electronics (nick named the peanut board)

- This board worked as intended.
  - Modifications were made to adjust mounting on the x axis for the next revision, it needed to be closer to the preload to improve the depression force against the pogo pins.
  - This revision did not have electronics board on the docks.



4.0 Second revision

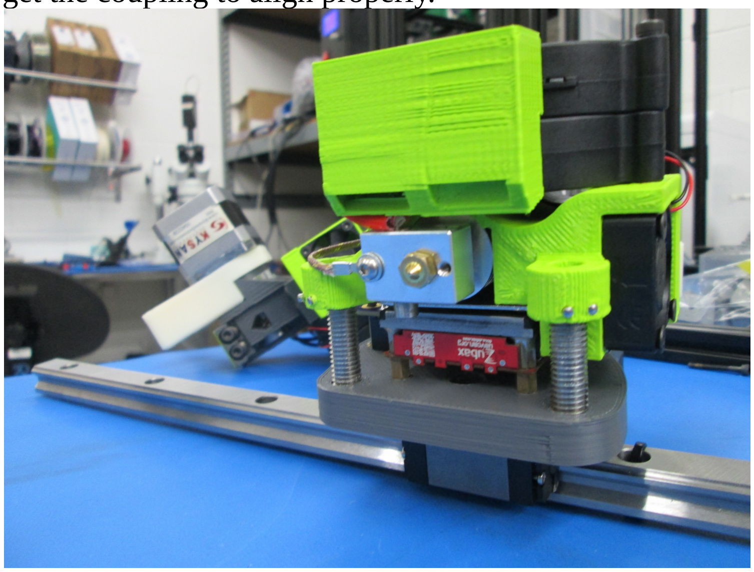
Revision improvements/tests include decreasing the overall footprint of the toolhead, reducing the weight of toolhead, pelonis blowers, fan shrouds, printing with two toolheads, new idler system, kinematic coupling, using toolheads that have different z heights, simple x y printer configuration (first revision used core x y), and a new EPM mount. Details of part changes and results are listed below.



a) Pelonis extruder blowers and fan shroud.
   - Was successful but needs a few improvements.
     - Was able to mount in a position that would be impossible for a open air fan.
     - Both extruder fans were mounted behind toolhead to decrease size and allow toolheads to pass underneath each other in the docks.
     - Put out a massive amount of air coming from the back side of nozzle. It did not perform as well as a shroud that directs air from multiple directions.

b) New idler system.
   - Functioned well but ended up being replaced by Titan Aero.

c) Kinematic coupling.
  - Worked fairly well for first try, this was based off of Brent's design using pins hammered into plastic and long cone shaped set screws.
    - Unfortunately this kinematic coupling setup was inconsistent. Since the two toolheads were printed parts, there was enough variance between them to cause issues during pickup and drop off. Printed parts can flex slightly, which is not ideal for kinematic coupling. Kinematic coupling requires a flat plane to be accurate. Another issue with this rev. was the docking platform ended up with a large tolerance stack up, making it hard to get the coupling to align properly.



d) Toolheads with different Z heights (E3dv6 and E3d Volcano).
  - This test was successful.
    - We had to create custom g code to change the z height when swapping toolheads but this could be done automatically using the push button switch and saving the z offset values to memory on the toolheads.

e) Simple x y motion system.
  - Had one difference from core x y.
    - Since y axis is driven with independent motors there is a chance for the x axis to skew when motors are idle. A skewed plane makes it impossible to pick up the toolhead from the dock without realigning the axis.
    - This was not a problem on core x y as long as the belts were equally tensioned.

f) New EPM spring mounting.
  - Worked fairly well to pick up toolhead when things didn't align properly
    - Was hopefully just a temporary fix for this revision. This helped account for tolerance stack ups, and alignment issues.
    - May be worth pursuing in future revisions if alignment issues are still present.

g) Toolhead onboard electronics.
  - We got it to work eventually.
    - Problems were mostly related to occasional misalignment of pins. Hopefully these can be fixed mechanically in future revisions.

        - During docking we turn off the extruder fans and turn down the motor current to avoid shorts or arcs between pins.
        - The 5v fan output cannot be turned off during swapping. During poor toolhead swaps, we would get debounce that would occasionally fry the board. Caps were added to help dissipate the large debounce spikes. Making the docking more consistent will be the best way to alleviate this problem.

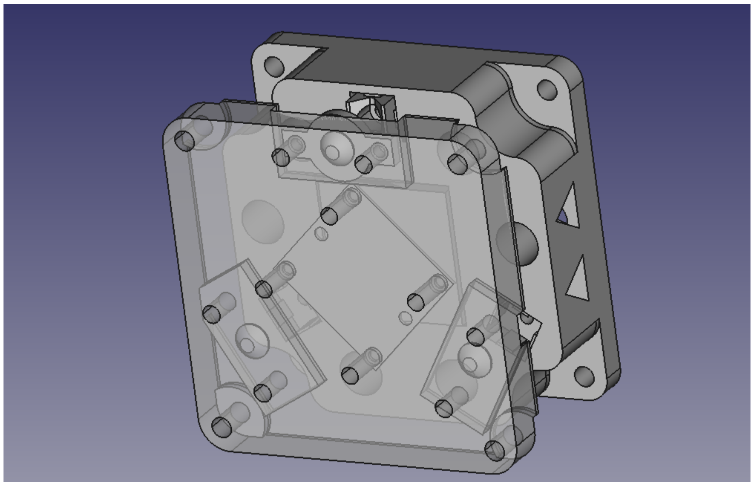
h) X axis and docking board.
    - Worked as intended for this rev.
        - Additional caps were added to dock for the 5v line. This hopefully wont be needed in the next revision.

5.0 Other testing notes

These are other tests done independently of the toolhead revisions, they include docking constraints, kinematic coupling, and Titan Aero testing.

a) Docking constraints.
    - Spring loaded holding mount.
        - Replaced the spring with one that has less spring force.
    - Alignment Pins.
        - Originally ordered for kinematic coupling but they over constrained the design.
        - However using a single one of these pins and a magnet, we could align the toolhead in the dock.

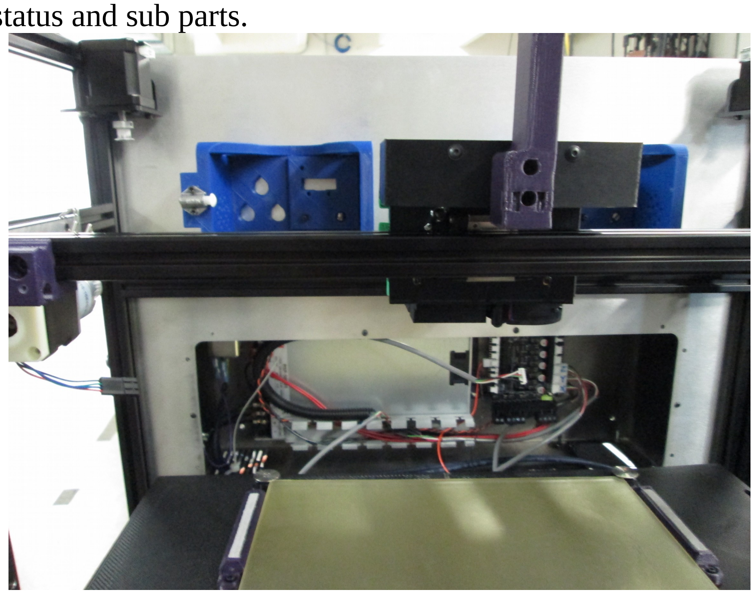
b) Kinematic coupling.
    - Tested a number of different components and configurations.
        - Components.
            - V-grooves seem like the best option for the female side. As v-grooves wear they will not loose accuracy. Pins are another option but I worry they may wear quickly and cause issues, especially since toolhead swapping can happen thousands of times per print. The pins we tested had a large amount of flex when connected, which is not ideal for accurate kinematic coupling.
            - Cones or balls are the best choice for the male side of coupling. Cones will hold heavy loads better, but this seems unnecessary considering light weight of the toolhead. Balls will be less expensive and many already have tight tolerance specifications off the shelf. I would recommend using balls at this point.
        - Spacing.
            - The second revision had the kinematic coupling mounts close together.
            - After testing different spacings for the mounts, I found it was significantly more stable using a 70mm triangle.
            - The distance the EPM needs to be from the connecting surface is less than .5mm for the magnetic field to pull it in. Using machined parts for the two planes that hold the kinematic coupling, we might be able to get it consistently under .5mm. If this is to difficult, we can use springs on the EPM to compensate. However, if springs are used, our preload for the kinematic coupling will be dependent on the force of the springs instead of the EPM holding force (spring force will be significantly less).



c) Titan Aero.
   - Testing went extremely well, printing everything we could throw at it.
     - Built up a concept of revision 3 that was tested on a R&D motion study test fixture.
     - The compact size and build quality of the Aero will greatly aid in the design of the 3rd revision.

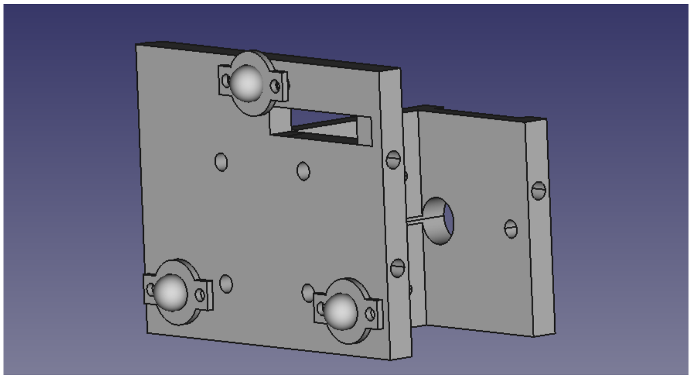
6.0 Current revision

This section highlights the current state of this system in its 3rd revision. This revision uses data gathered from previous revisions and other tests mentioned in section 4.0. The electronic boards for the toolhead system still need to be changed in order to fit different mounting schemes. There are preliminary holes cut where the boards might go but this still needs to be figured out. The freecad models for this revision are larger than intended, so they can be 3d printed for concept testing. The end goal is to have critical parts made of metal. The parts are purposely box shaped so we can use raw metal stock shapes to keep costs down (90 degree angle, U-bars, T-Bars). This section will list the parts material type, design status and sub parts.



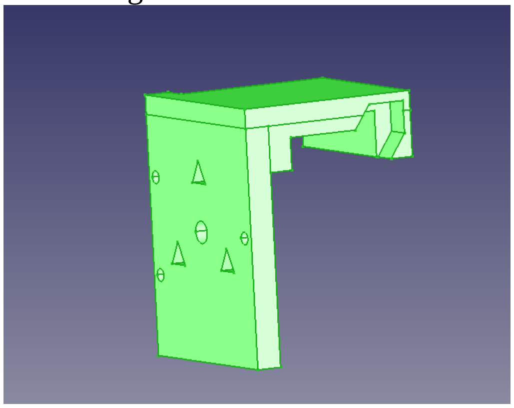
a) Carriage h mount.
   - 6061 Aluminum T-Bar or Metric Flat bar stock 6-8 mm thick.

- This parts shape is a lower case h it needs to be separated into multiple parts, either a T shape or flat bar before it is machined. Originally, the entire part was going to be steel so the EPM could attach. It will be less expensive to have a separate steel target plate the magnet can contact.



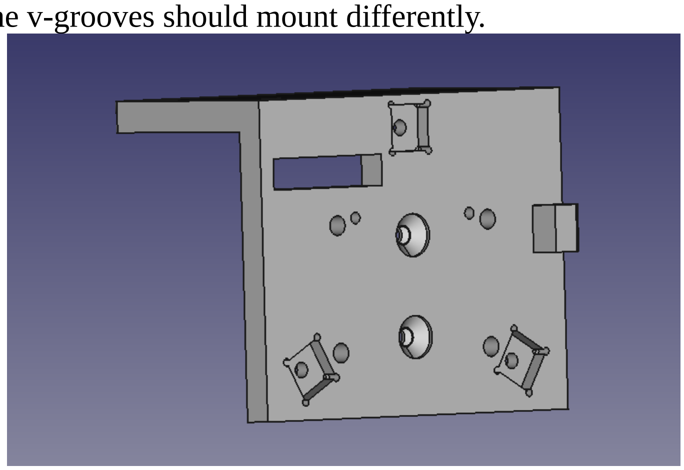
- Sub parts.
  - 3 balls.
    - Hardened stainless steel.
      - Since these parts will undergo an extremely high number of cycles we want them to be non corroding. These should be fairly easy to source since they are commonly used in bearings. They can be coated if needed to decrease friction and increase repeatability.
  - Ball holder cover.
    - 3d Printed ABS.
      - These keep the balls from falling out and allow them to spin freely. Having these machined is not necessary.
  - Magnet target plate.
    - AR400 carbon steel 1/8 inch or 3.175mm.
      - Picked a material that does not wear easily but it might be over kill. Low carbon steel should also be tested as a less expensive alternative.

b) Cover toolhead carriage.
- 3d Printed ABS.
  - This not a structural part, it will cover the toolhead electronics board, guide extruder blower intake air and hide/guide toolhead wires.



c) Carriage h mount (detached part).
   - 3d Printed ABS or aluminum.
     - This holds alignment pin for dock, magnet target plate and the Titan Aero extruder. Might want to consider making this out of aluminum since it will be structural.
   - Sub parts.
     - Alignment pin hole.
       - Steel Mcmaster part.
         - Aligns and constrains two axis of toolhead in dock.
     - Magnet target plate.
       - Steel plate.
         - Currently, the toolhead can pivot in a couple of axis while docked. Mounting this plate in the corner of dock should help constrain this without adding more parts.
     - Titan Aero toolhead assembly.
     - Pelonis blower and blower shroud.
       - 3d Printed ABS.
         - These will attach to carriage h mount, carriage h mount(detached), and cover toolhead carriage.
           - The 360 airflow works better than any of the previous fan shroud designs. It does need to be remodeled so that it is farther away the heater block. Having a wider range around the nozzle that the air hits might improve prints.

d) EPM attachment plate (on x axis).
   - 6061 Aluminum 90 degree angle 6-8 mm thick.
     - This should be the same thickness as the carriage h mount. Current model is designed to work with v-groove parts on hand for a 3d printed mount. When the metal part is created, the v-grooves should mount differently.

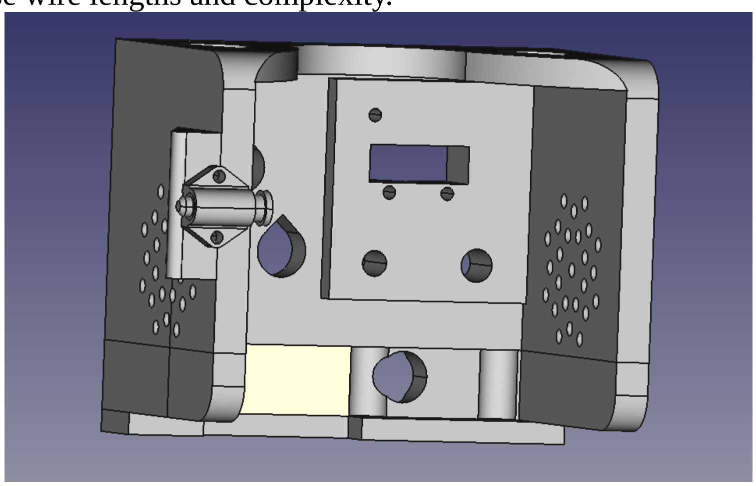


   - Sub parts.
     - 3 v-groove mounts.
       - Hardened stainless steel.
         - Different ways of getting this machined inexpensively should be explored. Options include 3 separate parts, 3 grooves in a single piece, and separated sides 3 pairs (6 parts).
     - EPM.

        - Tyler and Mark have more information on this.
          - New mounting schemes, plate, electronics and board size. The new EPM will be easier to mass produce and assemble.

e) Carriage cover.
  - 6060 Aluminum U-channel.
    - This piece can be fairly thin, it will hold the belt and cover the EPM electronics board. Depending on how emissions go a separate piece might needed for the bottom to completely enclose EPM board.

f) Dock.
  - This model may need to be separated into printed and machined parts. 6061 Aluminum U-channel.
    - I would recommend thicker 6061 for base since it will see wear and structural strain from continuous tool changing.
    - Toolhead still needs to be constrained better, mounting the magnet in the top corner of dock may help constrain remaining axis.
    - In the next prototype revisions we plan to have this mounted to the electronics box to decrease wire lengths and complexity.



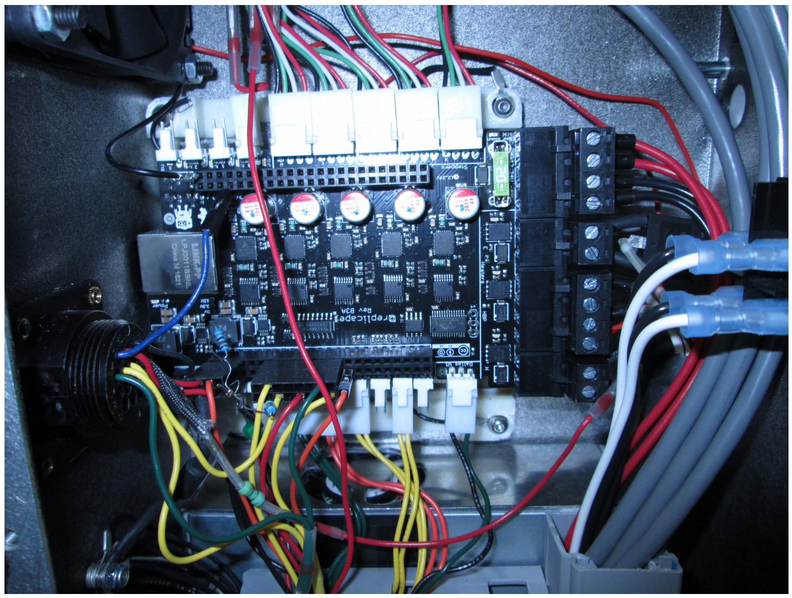
  - Sub parts.
    - Spring stop.
      - This is an off the shelf part from Mcmaster.
        - Works really great for keeping the toolhead in dock. Only change I made was changing the springs out for ones with less force. Making our own version of this in-house is an option.
    - Alignment pin male.
      - Steel Mcmaster part.
        - Aligns and constrains some axis in toolhead in dock.
    - Permanent magnet.
      - This still needs to be tested to decide the best option.
        - The main function of this is to pull toolhead into the docking pogo pins. It needs to be strong enough to depress the pogo pin springs but not so strong that the EPM can't pull it away from the dock.

7.0 Electronics and firmware

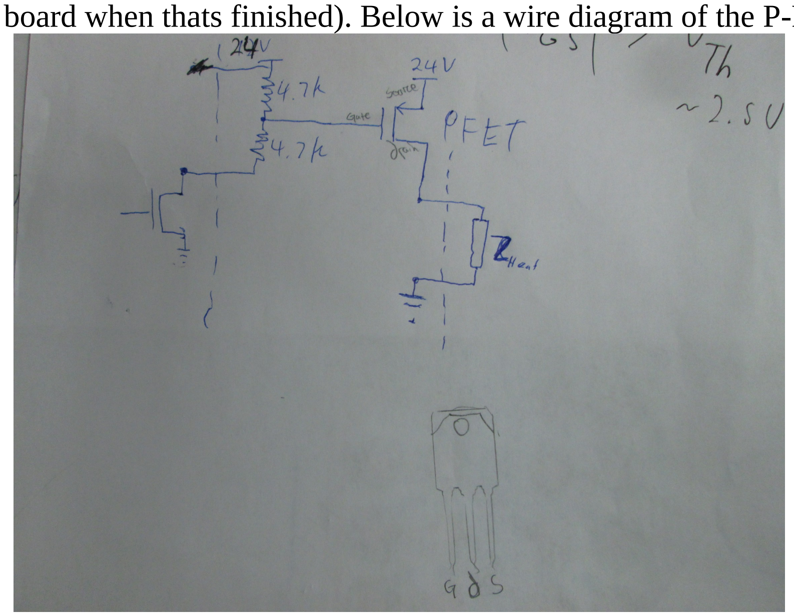
If octoprint and redeem do not start after 5 min you may have to power cycle the machine to get it running. This will need to fixed in future. It seems to be happening during the restart, I would begin by looking at the network settings, there is a time window where it is trying to discover a DHCP server and after it times out it occasionally becomes unresponsive.

7.1 Wiring

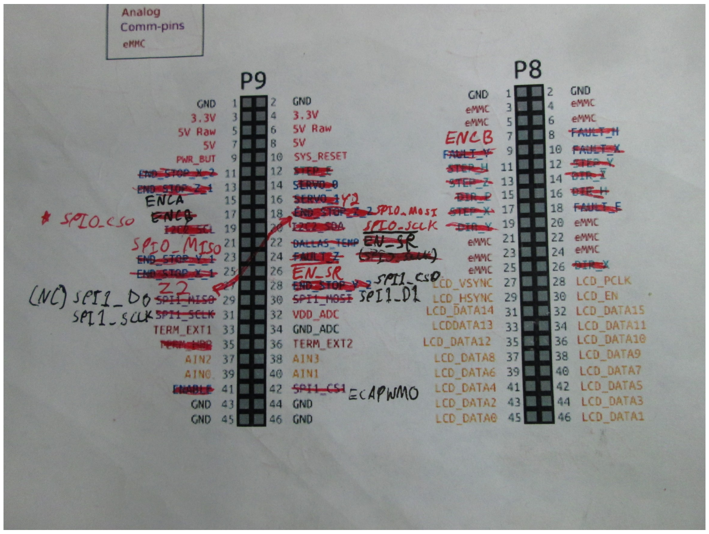
I will go over basic explanations of wiring for toolhead swapping, you can use the second revision test fixture for reference.



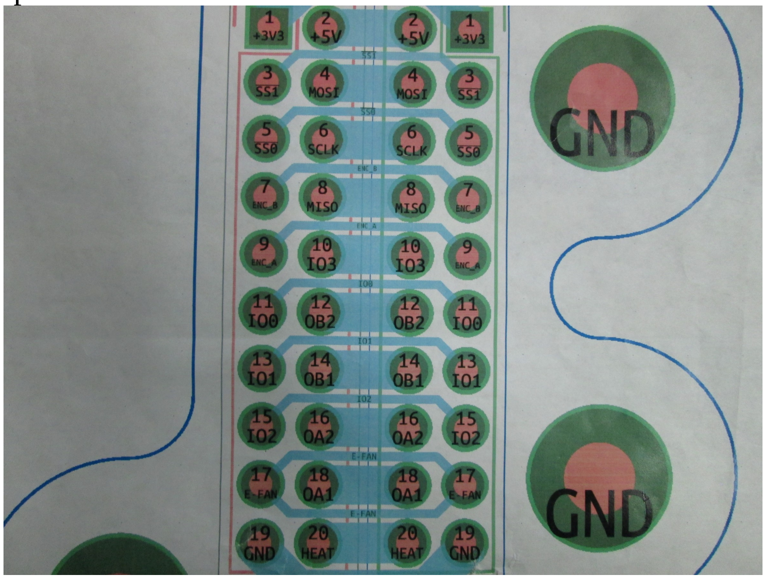
a) P-FETS are used on the two 24V connections to the toolhead (this wont need to be done on the development board when thats finished). Below is a wire diagram of the P-FETS.



b) Custom pin-outs on Beaglebone/Replicape are listed below. These are used for communicating with toolhead electronics board.



c) Docking board pin-outs below.



d) All grounds for toolhead are unified so there is no need to run an extra wire to the heater block for probing/auto-leveling.

7.2 Redeem configuration

The configuration file for the second revision is here: left click. This should be a good starting point for making the firmware work on an Athena prototype.

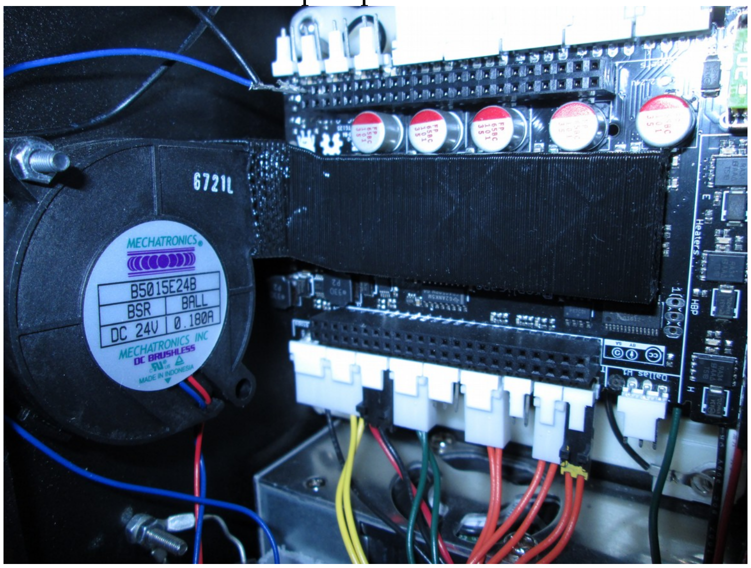
a) Controlling the EPM pwm through g code.
   - Logic from servo control is used to pwm the EPM through g code, an example is at the bottom of the config file under g code macro g31.
   - Wait commands were put between toolhead swaps to account for the time it takes the EPM to cycle.

- M574 y commands turn the y endstop on and off to access the docking section for toolhead swapping. This is so users can't run into docks during manual movements and it gives us more accurate positioning coordinates for printing, wiping and calibrating. An area without the docks will also make it easier to integrate into existing slicers.

7.3 Stepper Drivers

The Replicape uses the TMC2100 stepper drivers. Future boards are planning to use the TMC2130 stepper driver, it has a new mode that combines two modes on the TMC2100. The modes that we want to combine are stealthchop and spreadcycle which will hopefully give us a low current, silent stepper configuration.

a) TMC2100 stepper drivers.
   - "Decay" settings in redeem reference the chopper configurations in TMC2100 data sheet.
   - We are using microstepping mode 8 on the Replicape for the x and y axis (16th step interpolated to 256 microsteps) this will give us smother motion, silent steppers and better looking prints. More information on this is available by reading documentation on the TMC2100. Link to document: left click. Link to Redeem wiki: left click.
     - Running the steppers in stealthchop will limit how fast we can accelerate/decelerate unless we greatly increase the motor current. This is explained in the TMC2100 data sheet on stealthchop "It measures the actual current with each fullstep and subsequently does a limited correction of the PWM voltage. Therefore, at high acceleration or deceleration, the internal regulation might not react quickly enough to stabilize the motor current within a range near the target current". So this means the motor current lowers as it accelerates and rises as it decelerates and if the current deviates too much it will not have the required amount of torque to accelerate and skip steps. Increasing the motor current above 0.5A will require the use of active cooling directly on stepper driver chip (see fan shroud created for test fixture printer below as an example). After testing I determined the motor current would need to be increased to 1.0A at present acceleration in order to not skip steps.



- The remaining stepper drivers are set in mode 4 on the Replicape (16th step), the extra resolution gained by mode 8 will not provide the same benefit to gear reduced motors and they need the extra torque (z1, z2, z3 and e1).

b) TMC2130 stepper drivers.
- This stepper driver is very similar to the TMC2100 but with some new features. The feature we are most interested in is a mixed mode of stealthchop and spreadcyle. The 2130 should be able switch between these modes based on the movement velocity so during high velocity movements it would switch to spreadcycle. Potentially with this mode we could drop the motor current low enough to not require active cooling.

7.4 Auto calibration and true auto leveling

Auto calibration and true auto leveling features will be key in setting this printer apart from others.

a) Auto calibration.
- Calibrating offsets between toolheads has been left up to the consumers by the 3d printing industry. Measuring with rulers or sight when your not sure what you're looking for can create headaches and bad prints.
- Using the proven nozzle auto leveling procedure on the TAZ and Mini we can utilize this for calulating offsets in x and y. After x and y are auto calculated we can store that offset on each toolhead's onboard memory.
- Early concepts have been made touching a square aluminum block with the nozzle.
- This still requires a good amount of development and testing.

b) True auto leveling.
- Most of the industry uses mesh leveling or auto tramming (commonly just called auto leveling) to adjust for the first layer of a print. This is great for getting an even first layer but ultimately an unleveled bed will lead to less dimensionally accurate parts.
- By leveling the entire plane of the bed it will make the axis exactly perpendicular and give you the most dimensionally accurate parts.
- Using 3 independently driven motors in z we can use nozzle probing at 3 points to adjust the bed in x and y.
- We have successfully tried this in x on the test fixture printers.

8.0 Useful links and file locations

Repository links include change history of files throughout development. To follow file paths online use this link: click here

a) First working concept toolhead files location.
- devel/lulzbot/research_projects/big-thompson/direct_drive_tool_head_mechanical
- Repository: click here

b) Second revision files location.
- devel/lulzbot/research_projects/big-thompson/small_toolhead_for_swapping
- Repository: click here

c) Kinematic coupling test fixture.
- devel/lulzbot/research_projects/big-thompson/kinematic_testing
- Repository: click here

d) Current revision files location.
   - devel/lulzbot/research_projects/athena/pre-evt_prototypes/production_parts/athena_toolhead_revision
   - Repository: click here
e) EPM source information
   - click here
f) Replicape board wiki
   - click here
g) Redeem
   - Original Repository: click here
   - Modified branch for toolhead swapping: click here
h) Videos and photos of prototypes in action.
   - devel/lulzbot/research_projects/video
   - devel/lulzbot/research_projects/photo