Furious Build Notes

By McMaven

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1 Overview

I modeled this design after a Jacob and Co. Twin Turbo Furious, which they offer in several of their high-end watches. I spent many hours looking at this video https://www.youtube.com/watch?time_continue=2&v=n4DxzTQBTSM .

Similar to the Gyrotourbillon and the Triple Axis, I tried to make the model an accurate (scaled up) version of the original Furious mechanism. I printed the screws to scale and used them as caps to cover the 2mm screws that actually hold it together.

In looking at the videos of this design, there mechanism with a spring between two plates (shown below). I'm don't know what its original intent was, but I'm using it to decouple the intermittent rotation of the movement (you can see the balance spring below the trellis) from the constant rotation generated by the stepper motor. Without it the L2 spherical frame would jerk with every tick. The spring and the lower silver plate attach to the movement assembly. The end of the spring is attached to the upper silver plate with that Philips head screw, which is driven by the motor. And there is a pin below the screw that sticks into the slot in the lower plate. In the picture the assembly is at rest, so the spring has pulled the pin to the right end of the slot in the lower plate.
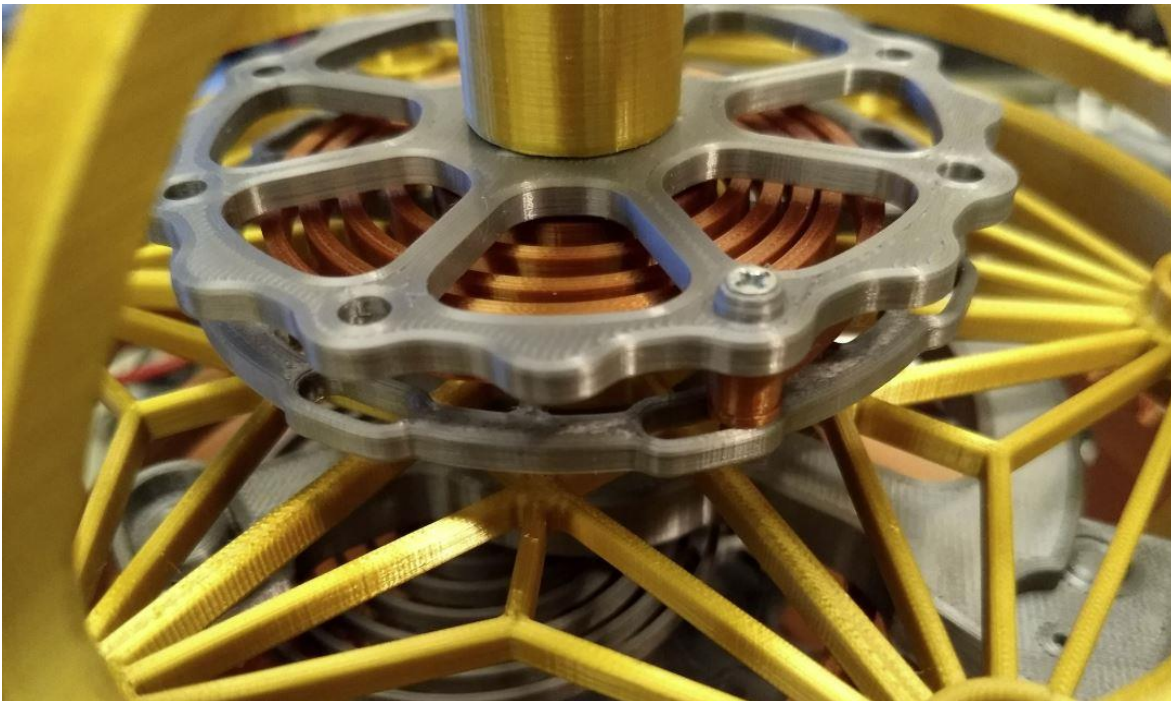
When I turn on the stepper, the end of the spring slides in the slot to the left, and the spring passes torque to the (L1) movement assembly so it can tick. When the speed of the motor matches that of the movement, the pin of the end of the spring moves back and forth in the middle of the slot. If the speed of the motor is slow, then eventually the pin moves to right end of the slot and the movement stops ticking. If the speed of the motor is fast, then the pin moves to the left end of the slot. When it hits the left end of the slot, there is a step function in the torque and the things can go bad very quickly.

This is because there is a torque overload when the end of the slot is hit, the torque overload passes too much energy to the balance wheel (sort of kicking it) causing to swing further, which reduces the tick frequency and average rotation rate of the movement assembly. The symptoms are that the movement suddenly starts ticking very loudly, and the movement quickly binds. The sudden drop in the rotation rate of movement aggravates the overload condition, which if ignored can break shafts or teeth of gears. The one time I didn't stop the motor in time, the main shaft sticking out of the L1 Frame Bridge broke.

 I can watch the watch the position of the pin in the slot as it goes around, and tweak the motor speed to keep it centered. The problem is that there is a huge delay in the response time to changes in motor speed, so it's easy to over correct and lose control.

The code using sets the initial speed very low, so when I turn on the stepper, it starts at a really slow rotation rate and this design needs a much faster rate. So I have to crank the shaft encoder like mad to get it up to the speed, and at the same time I bump the balance wheel to make sure it doesn't hang and break some gear teeth or something else. So for all practical purposes, you have to kick start it like an old hit-or-miss engine, then carefully tend it to keep it running. I actually found it sort of a challenging to find the speed sweet spot. So I decided to post the design as is, explain the issues, and see if anyone comes up with a solution.

Other learnings...

At one point I squeezed the outer edges of the L2 Upper and Lower Bodies together too hard, and I broke the shaft sticking out of the L1 Frame Base. My solution to this and the L1 Frame Bridge shaft breaking was to design a 3mm hole in the center of each shaft, that I could slip a 3mm steel rod into.

This was also my first experience with 'silk' PLA filaments, and there was learning curve. Using the same settings that I have been using forever for regular PLA, the first layer didn't want to stick to the print bed, and I found that it has relatively poor inter-layer adhesion. To address the layer 1 problem I tried changing the print bed temp from 60 to 70 C°, but it did not seem to be very effective. What worked was a lower the Z height on the first layer to get a lot more squash to it. To address the inter-layer adhesion problem, I turned up the extruder temperature 10, but again this did not make a big difference, however the parts seemed a little stronger when I changed the perimeter layer count from 2 to 3.

A lot of people complain because silk filaments clog their nozzles. I printed all the parts for this design without a clog, however shortly after I switched to normal PLA to print the base I got my first clog ever, and that's with over 2000 hours of print time on the same 0.4mm brass nozzle. I used it as an excuse to finally put a new nozzle in. I have no idea if the silk PLA had anything to do with it, but it seemed like a weird coincidence.

This model is LARGE, at over 200mm in diameter. And it's powered it with a 2 Amp USB power supply.

And a real-time video. https://youtu.be/Imm3mrR06tc

2   Parts list

Here are the parts that I used. You can use hex socket or Philips head screws, your choice. I paid about $1 a piece for all the ball bearings on eBay or Amazon.

Some of the "2mm" steel shafts that I've picked up on eBay or Amazon have been slightly oversized, just enough so the bearings won't fit on to them. Look for a slip fit of the shaft in the bearing. DON'T force the bearings on the shaft. Excess force can jam the bearings, making them useless. My solution was to order shafts from another vendor. Maybe you will get lucky the first time.

2.1   Summary

(6) 2x5x2.5mm MR52-ZZ ball bearings

(6) 8x12x3.5mm MR128 ball bearings

(1) 20x27x4mm 6704-2RS ball bearing

(1) Miniature Axial Ball Thrust Bearing F8-14M (8x14x5mm)

(16) 6mm steel balls

(~70mm) 2mm shafts

(~100mm) 3mm shafts

(1) Arduino Nano

(1) 28BYJ-48, 5 Volt Stepper Motor with driver board.

(1) 2A USB Power Supply

(1) USB Mini-B to A cable.

Screws, see section 2.2.

2.2   Details

2x5x2.5mm ball bearings

- 2 for the L1 Fork

- 2 for the L1 Escape Wheel

- 2 for the L1 Balance Shaft

8x12x3.5mm MR128 ball bearings

- 2 for the L1 Frame Base

- 2 for the L1 Frame Base Bridge Main

- 2 for the L2 Lower Body

2mm shaft

- 13mm long for the L1 Fork

- 22mm long for the L1 Escape Wheel

- 33mm long for the L1 Balance Shaft

3mm shaft

- 71mm long for the L1 Frame Base

- 23mm long for the L1 Frame Base Bridge Main

Screw Usage Table

Description	Total	L1	L2 Lower	L2 Upper	L3 Frame	Base	Base Driver
M2x6 flat head screw	3	3					
M2x8 flat head screw	24		7	1	10		6
M2x10 flat head screw	11	3				8	
M2x12 flat head screw	2				2		
M2x14 flat head screw	1			1			
M2x4 button head screw	2						2
M2.5x6 button head screw	8						8
M2.5x4 button head screw	2						2

Bearing Usage Table

Description	Total	L1	L2 Lower	L2 Upper	L3 Frame	Base	Base Driver
2x5x2.5mm MR52-ZZ	6	6					
8x12x3.5mm MR128	6	4		2			
20x27x4mm 6704-2RS	1		1				
8x14x5mm Thrust Bearing F8-14M	1			1			
6mm Ball Bearing	16					16	

3   Components

The following images identify where the parts go in each layer.

I used *Screw 8mm* and *Screw 9mm* parts to simulate the screw tops on the original mechanism. In most cases I ran a M2 mm flat head screws through them and the parts that they needed to connect together (e.g. the *L1 Frame Upper* and *L1 Frame Lower*, or the *L1 Frame Lower* to the *L1 Bridge* and the *L1 Lower Escape Bridge*), and used *Screw Seat 8mm* parts as a 'nut' to screw them into. I didn't use glue on the Screw Seat 8mm nut parts because they were a press fit.

3.1   L1

I drilled out the center of the L1 balance Shaft with a 2.5mm drill to ensure that the shaft would not bind. Press fit the L1 Balance Wheel to the L1 Balance Shaft, then the L1 Balance Spring to the L1 Balance Wheel. The hex surfaces on these parts are undersized, so they must be filed to provide a slip fit. In the process of setting up the movement I disassembled them many times, so make sure the fit isn't too tight. I didn't do this and I broke the hex shaft off the Balance Wheel when I tried to remove the Balance Spring. But it might have been due to the poor inter-layer adhesion of the silk filament.

Press a 2x5x2.5mm MR52-ZZ ball bearings into each end of the Balance Shaft, the Fork and the Escape Wheel shafts. You might have to run a knife around the edges of the bearing holes to make it easier to press them in.

Insert the 13mm long 2mm shaft into the L1 Fork, the 22mm long 2mm shaft into the L1 Escape Wheel, and the 33mm long 2mm shaft into the L1 Balance Shaft.

Then press a *2x1mm Bearing Spacer* into each end of the Fork and the Escape Wheel shafts, and on to the end of the Balance Shaft that engages with the fork. On to the other end of the *Balance Shaft* press the *L1 Balance Spacer*. You might have to file the Bearing Spacers a little to get them to fit.

Run a 2mm drill backwards into the holes in the *L1 Frame Base Bridge Main*, *L1 Frame Base Bridge Inner*, and *L1 Frame Base* holes that will receive the L1 Balance Wheel, L1 Fork and L1 Escape Wheel shafts, to clean them out. Be careful not to drill through the *L1 Frame Base Bridge Inner*, and *L1 Frame Base* holes.

Press the 23mm long 3mm steel shaft into the end of the *L1 Frame Base Bridge Main* shaft, and the 71mm long 3mm steel shaft into the *L1 Frame Base* shaft. The steel shafts help make the respective plastic shafts stronger. Both steel shafts should be flush when fully inserted.

Glue the three *Jewel 6mm* parts into the *L1 Frame Base Bridge Main*. These support the ends of the 2mm, L1 Balance Wheel, L1 Fork and L1 Escape Wheel shafts.

Glue three *Screw 9mm Seat* parts into the *L1 Frame Base Bridge Main*.

Glue two *Screw 12mm* parts to the *L1 Frame Base*.

Make sure that the two *L1 Frame Base Alignment Pins* are a slip fit into their mating holes in the *L1 Frame Base Bridge Main*, then press them into the *L1 Frame Base*. They were a tight press fit in the *L1 Frame Base* with my prints, which allowed me to reuse them when I reprinted the part, but you may have to glue them.

Fit the Fork and the Escape Wheel with their shafts to the *L1 Frame Base Bridge Main*, then use three M2x6mm flat head screws to attach the *L1 Frame Base Bridge Inner* to the *L1 Frame Base Bridge Main*. At this point check that the surfaces of the *L1 Frame Base Bridge Inner* and *L1 Frame Base Bridge Main* are parallel. If one of the 2mm shafts is slightly too long, it can cause the *L1 Frame Base Bridge Inner* to bend away from the *L1 Frame Base Bridge Main*.

Fit the Balance Wheel assembly with its 2mm shaft to the *L1 Frame Base Bridge Main*, press the assembly on to the *L1 Frame Base* and use two M2x10mm flat head screws to attach them together.

In the slotted hole of the *L1 Frame Base*, insert the *L1 Balance Spring End Mount*, center it in the slot and orient it with its tab facing away from the end of the Balance Spring. Then through a *Screw 9mm w screw hole* part use a M2x10mm flat head screw to hold them together. Now press the end of the Balance Spring into the *L1 Balance Spring End Mount*.

Press two *Screw 7mm End Cap* parts into the *L1 Frame Base Bridge Main* part to cover the screws. Note that you may want to hold off on this step until after you are sure that the L1 Assembly is tuned. They can be a pain to get out if you need to disassemble the L1 Assembly.

Slip a 8x12x3.5mm MR128 ball bearing, the *L1 Bearing Spacer Lower*, and a second 8x12x3.5mm MR128 ball bearing, onto the *L1 Frame Base Bridge Main* shaft. Then do the same thing for the *L1 Frame Base* but use the *L1 Bearing Spacer Upper*.

Now the L1 Assembly is complete.

Figure 1: L1 Assembly Components
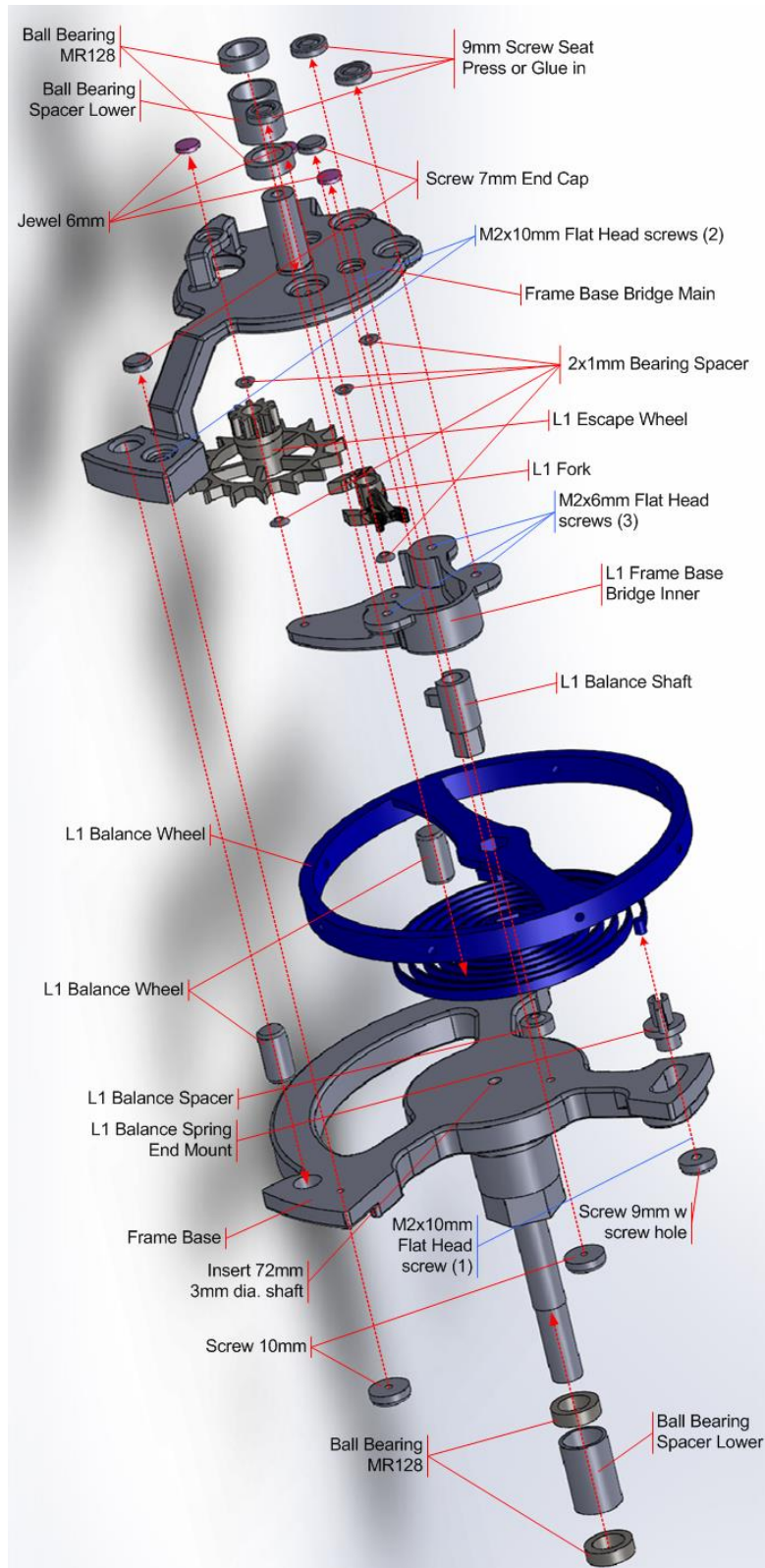
3.2   L2 Layer Lower

Check your bearing fits:

- Ensure that the 8x12x3.5mm MR128 ball bearings are an easy slip fit into the mounting holes in the L2 Lower and Upper Body parts.

- Ensure that the 8x12x3.5mm MR128 ball bearings are an easy slip fit into the shafts that stick out on either side of the *L2 Lower Body*.

- Ensure that the 20x27x4mm 6704-2RS ball bearing is an easy slip fit on the *L1 Frame Base* shaft of the L1 Assembly.

In each case it may require filing, sanding or grinding the inside of the mounting holes or the outside of the shafts.

Press the *L2 Drive Gear* on to the *L2 Lower Body*. You may have to glue it, but I found that a press fit worked well for me. Press fitting means that you won't have to reprint the *L2 Drive Gear* if you need to reprint the *L2 Lower Body*.

Press or glue six Screw 7mm End Caps in to the the *L2 Lower Body*.

Press the 20x27x4mm 6704-2RS ball bearing into the *L2 Lower Body Trellis*.

Fit the L1 Assembly into the *L2 Lower Body*. Then slip the *L2 Lower Body Trellis* onto the *L1 Frame Base* shaft of the L1 Assembly, and use six M2x8mm flat head screws to attach the *L2 Lower Body Trellis* to the *L2 Lower Body*.

Press six *Screw 12mm* parts into the *L2 Lower Body Trellis* part to cover the screws. Note that you may want to hold off on this step until after you are sure that the L1 Assembly is tuned. They can be a pain to get out if you need to disassemble the L1 Assembly.

Now the Lower L2 Assembly is complete.

3.2.1   To assemble the Upper L2 Assembly

Press one of the F8-14M Axial Ball Thrust Bearing races into the *L2 Upper Body*.

Glue the *L2 Upper Body Loading Plate Pin* to the *L2 Torque Spring*. Also you may have to file the sides of the *L2 Upper Body Loading Plate Pin* so that it slides easily in the slots of the *L2 Upper Body Loading Plate Lower* part.

Slip the *L2 Torque Spring Washer* onto a M2x14mm flat head screw, then use the screw to attach the *L2 Torque Spring* to the *L2 Upper Body Loading Plate Upper* part, and finally into the *L2 Upper Body Loading Plate Pin*. I would suggest holding the *L2 Upper Body Loading Plate Pin* with some pliers as you drive the screw into it, to reduce the chance of it breaking or twisting off. Note that the flange on the *L2 Torque Spring* should be against the *L2 Upper Body Loading Plate Upper* part when assembling.

Figure 2: Torque Spring
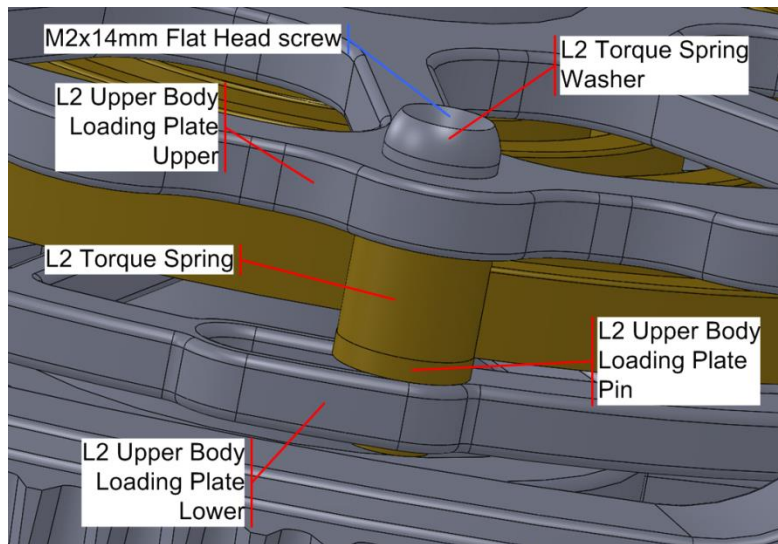
Note: the M2x14mm flat head screw is not shown in the image above.

Press the *L2 Upper Body Loading Plate Upper* on the *L2 Upper Body*.

Press the *L2 Upper Body Loading Plate Lower* on the *L1 Frame Base* of the L1 Assembly.

This is the tricky part. In the end you need to ensure that the hex in the center of the *L2 Torque Spring* mates with the hex of the *L1 Frame Base*, and that the Torque Spring is preloaded, which means that you need to twist the L2 Upper Body assembly to put tension on the Torque Spring. If everything presses together (possibly after some filing) and the *L2 Upper Body Loading Plate Pin* is in one of the *L2 Upper Body Loading Plate Lower* slots, lift it just enough to disengage the Loading Plate Pin and rotate it 3 more slots to the left, to put some tension on the Torque Spring.

You need to slide the L2 Upper Body Assembly on to the shaft of the *L1 Frame Base* and mate the hex in the center of the *L2 Torque Spring* with the *L1 Frame Base*. This will take rotating the L2 Upper Body Assembly while pressing them together, and maybe some pressing and pushing around of the center of the spring with a long thin screw driver to get it to slip on to the the *L1 Frame Base* hex. Then make sure

that the *L2 Upper Body Loading Plate Pin* is in one of the *L2 Upper Body Loading Plate Lower* slots and the Torque Spring is preloaded, as described above.

When properly assembled, the upper and lower L2 assemblies should rotate with respect to each other, the amount of rotation between them should be limited by the *L2 Upper Body Loading Plate Lower* slot and the *L2 Upper Body Loading Plate Pin*, and the Torque Spring should pull the Loading Plate Pin back to the right end of the slot (as shown above) when you let go of the L2 Upper Body Assembly.

## *Figure 3: L2 Layer Lower Assembly Components*
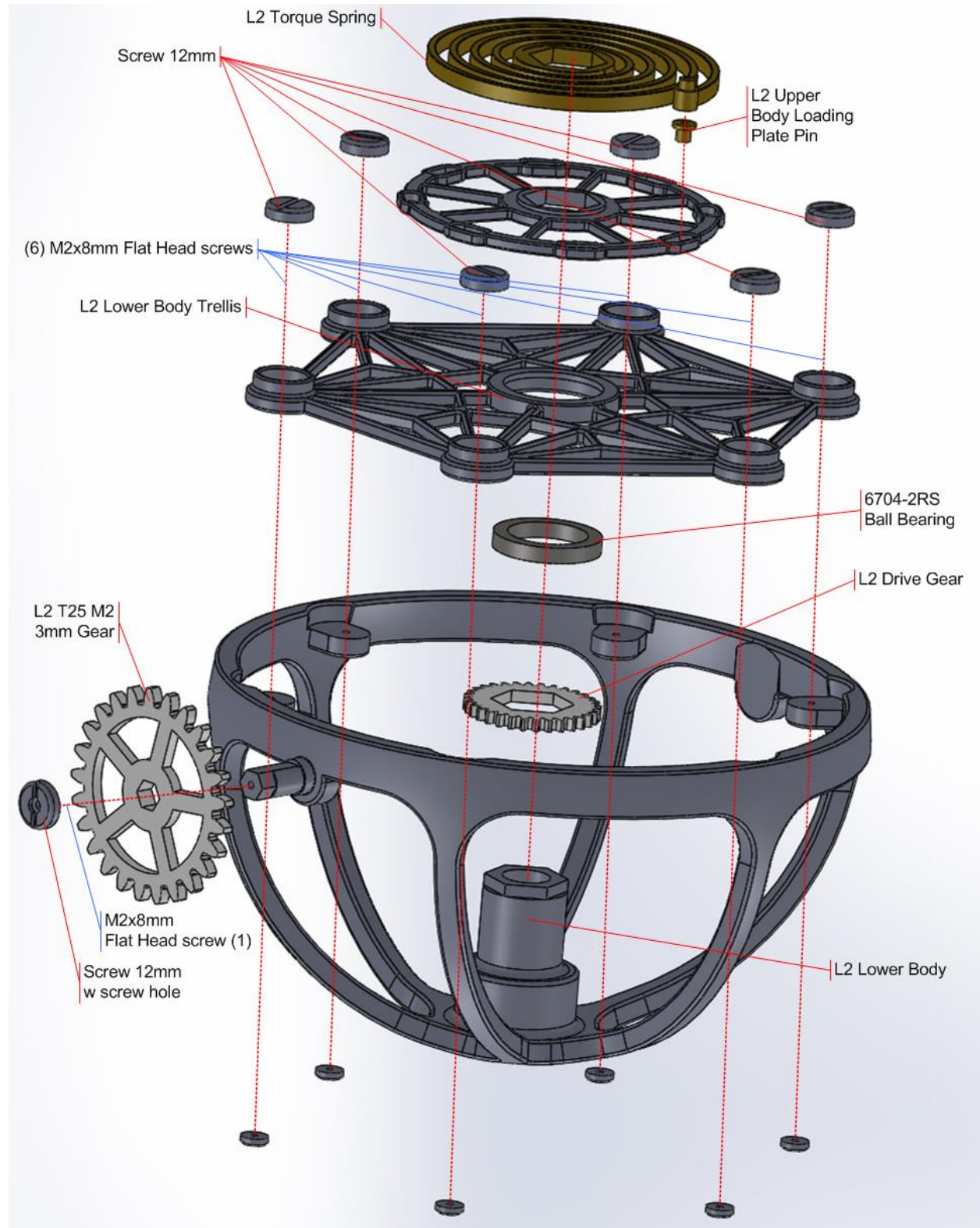
3.3   L2 Layer Upper

Press or glue the *L2 Upper Body Loading Plate Upper* to the *L2 Upper Body*. Be sure that the flange on the *L2 Upper Body Loading Plate Upper* faces away from the *L2 Upper Body*. The hex orientation doesn't matter.

The F8-14M Thrust Bearing comes in three parts, 2 races and a cage that holds ball bearings. One race is pressed into the L2 Upper Body. When the L2 Assembly is attached to the L1 Assembly; the cage, the remaining race and the L2 Thrust Bearing Washer are stacked on the race that was pressed into the L2 Upper Body, and attached with an M2x8 flat head screw. Note, tighten the screw just enough to allow the L2 Upper Assembly to spin freely on L1 Assembly.

Figure 4: L2 Upper Assembly Components
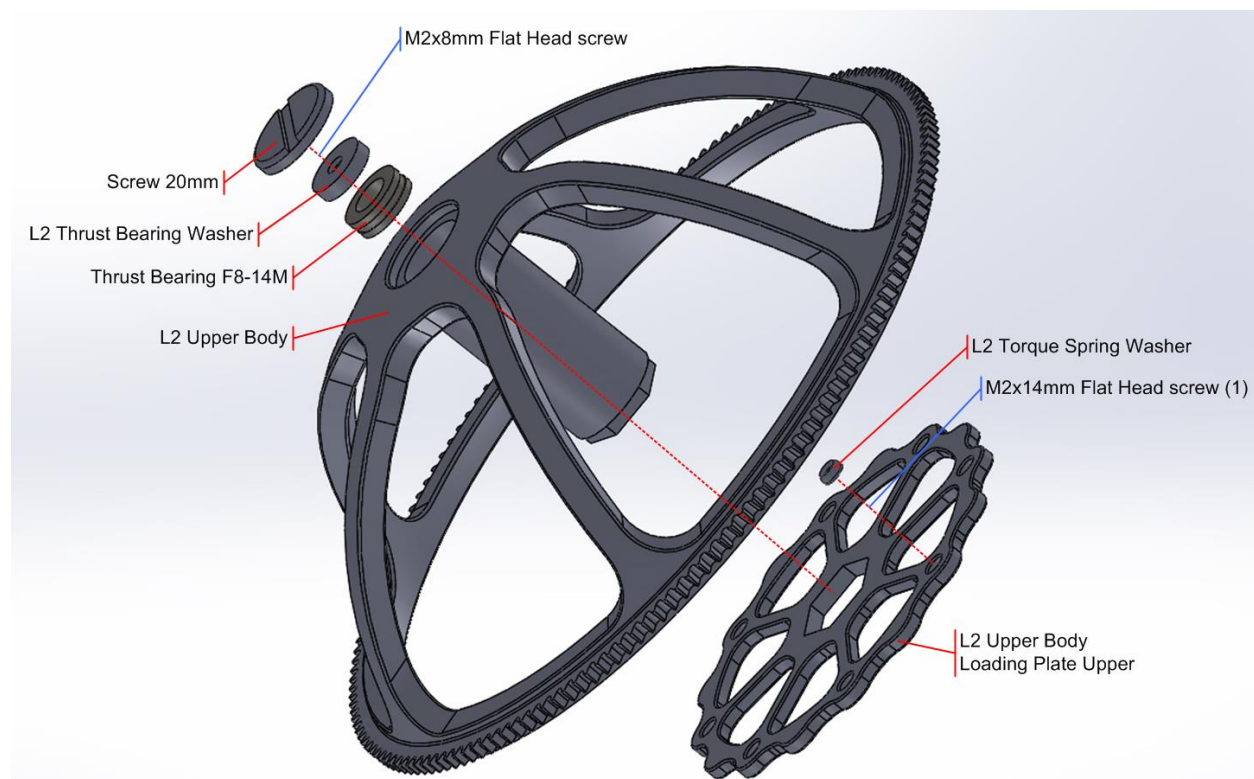
The *L2 Torque Spring Washer* is used when attaching the *L2 Torque Spring* to the *L2 Upper Body Loading Plate Upper*, as described in section 3.2.1.

3.4   L3

The *L3 Frame* is printed with supports. The *L3 Crown Gear* STL requires supports, however if you print the *L3 Crown Gear a* and *b* STL files, then you need supports for the *a* part, but not the *b.* And you will need to glue the two pieces together. The remaining parts can be printed without supports.

After inserting an MR128 ball bearing into the L3 Frame, the *L3 Crown Gear* can be screwed to the L3 Frame with 2 M2x8mm screws.

Use some fine sandpaper to smooth the *L3 Bearing Race Upper* and *Lower* races.

The *L3 Bearing Race Upper* part is a separate so it can be printed without supports to provide a smooth bearing race surface. Clean any residual support material off the L3 Frame and press the *L3 Bearing Race Upper* part on to it. You may have to scrape the elephant foot/flashing off the *L3 Bearing Race Upper* part to ease assembly. And lightly sand all the race surfaces to smooth them. The flat surface of the *L3 Bearing Race Upper* part should be flush against the bottom surface of the *L3 Frame*. Note any leftover support material will cause gaps, which can cause the race to bind.

Figure 5: L3 Assembly Components
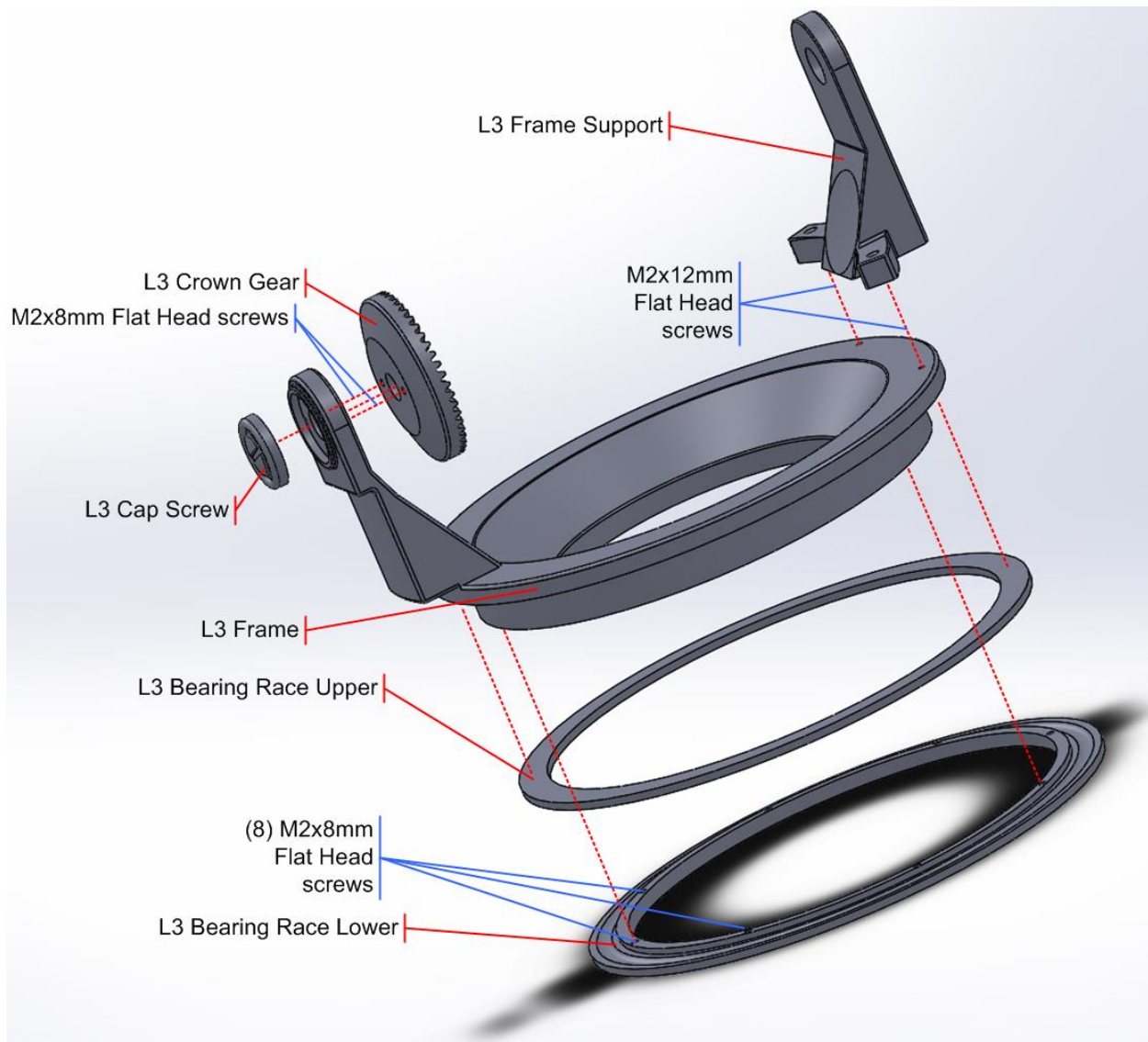
The *L3 Frame Support* is screwed to the *L3 Frame* when assembling the *L2 Lower Assembly*. And the *L3 Cap Screw* is pressed in, only after locking the L2 Lower Assembly in place by screwing the *L2 Crown Bearing Washer* to the end of the *L2 Frame Lower* shaft with an M2x8mm flat head screw.

3.5   Base

The *L3 Race Inner* STL requires supports and is included for SLS printers.

If you print the *L3 Race Inner a* and *b* STL files with the races facing up, then no supports are needed for the prints, and you should get a smoother bearing race surface on both parts. However you will need to glue the two pieces together. Make sure that the screw holes line up when you glue them together.

Glue them together with some 'Acrylic Cement' (see section *Some notes on gluing PLA…* below). This stuff is super volatile and works in seconds. So make sure you are ready to align the parts before you apply the glue.

Use some fine sandpaper to smooth the races.

Figure 6: Base Assembly Components
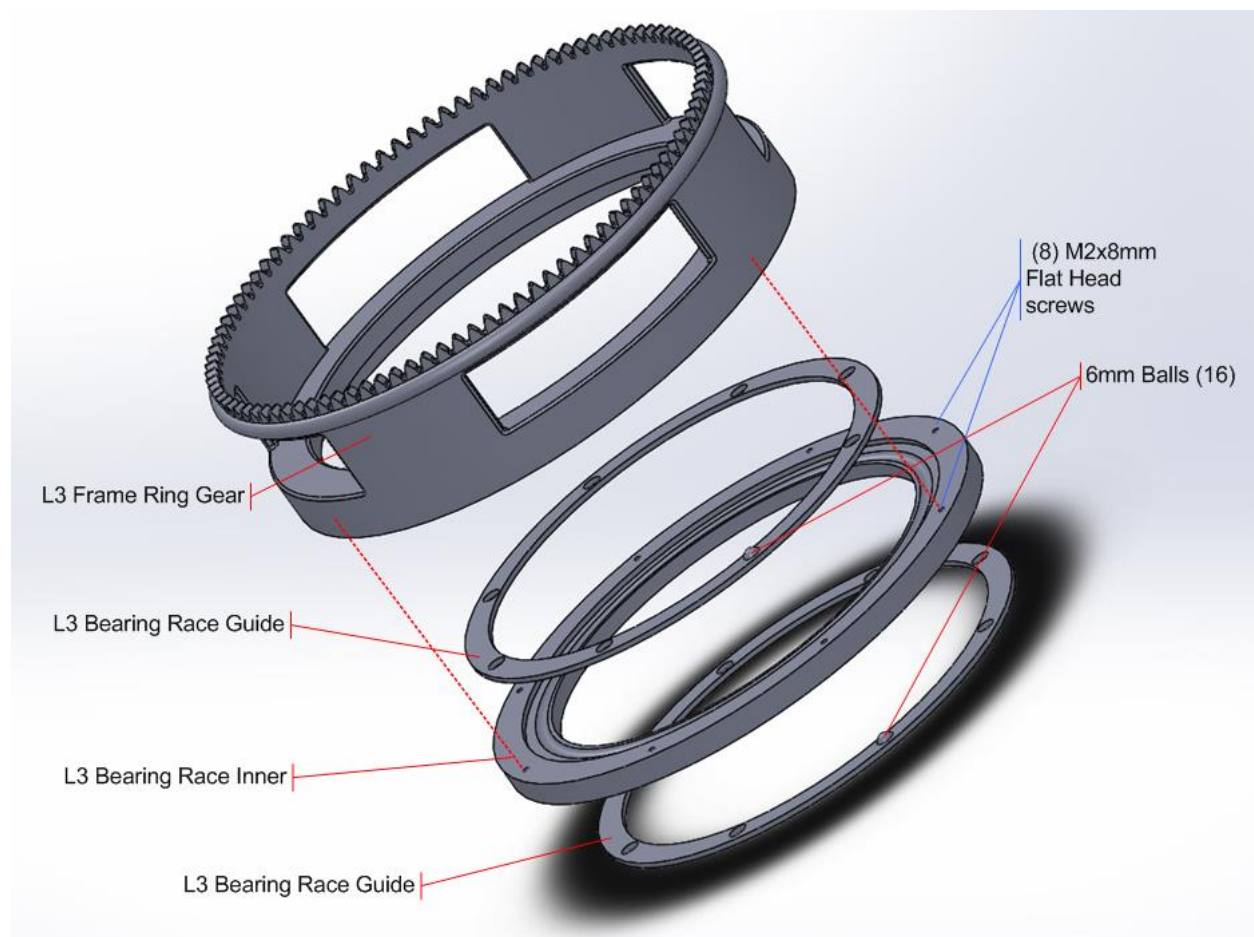
Make sure that the balls rotate freely in the *L3 Bearing Race Guide* holes (you may have to scrape or file away some flashing), and that the *L3 Bearing Race Guides* spin freely in the *L3 Bearing Race Inner* before attaching the L3 Layer Assembly.

Also make sure that the *L3 Bearing Race Inner* rotates freely in the *L3 Frame*.

Once the *Bearing Race Inner* is assembled, it is screwed to the L3 Frame Ring Gear with eight M2x8 flat head screws.

The *L3 Bearing Race Guides* and 6mm Balls are shown here but they are not used until the L3 Layer Assembly is attached to the Base Assembly.

3.6   Base Driver

Press the *Base Drive Inner Disk* into *Base Drive Plate*. You may want to glue this. With my prints this was very tight press fit, so I didn't bother.

Screw the Shaft Encoder PCB to the *Base Drive Plate* with two M2x4mm button head screws.

Screw the stepper motor to the *Base Drive Plate* using two M2.5x4mm button head screws. You may have to add some washers, so the screws don't extend above the *Base Drive Plate*. Note, if the screws extend above the *Base Drive Plate* they will jam the L3 assembly from turning.

Screw the stepper motor driver PCB to the *Base Drive Plate* using four M2.5x6mm button head screws.

Press the *Stepper Pinion* on to the stepper shaft.

The *Base Drive Outer Ring* was too big to fit on my print bed, so I split it into two parts *Base Drive Outer Ring a*, and *b*. I didn't glue these parts together. Use six M2x8mm flat head screws to attach the *Base Drive Plate* to the *Base Drive Outer Ring* parts.

I bent the Nano pins 90 degrees, so they stuck out on either side, and secured it using two M2x6mm button head screws. Then using jumper wires, I connected the electronics together. Refer to section 5 for the wiring diagram.

Figure 7: Base Driver Assembly Components
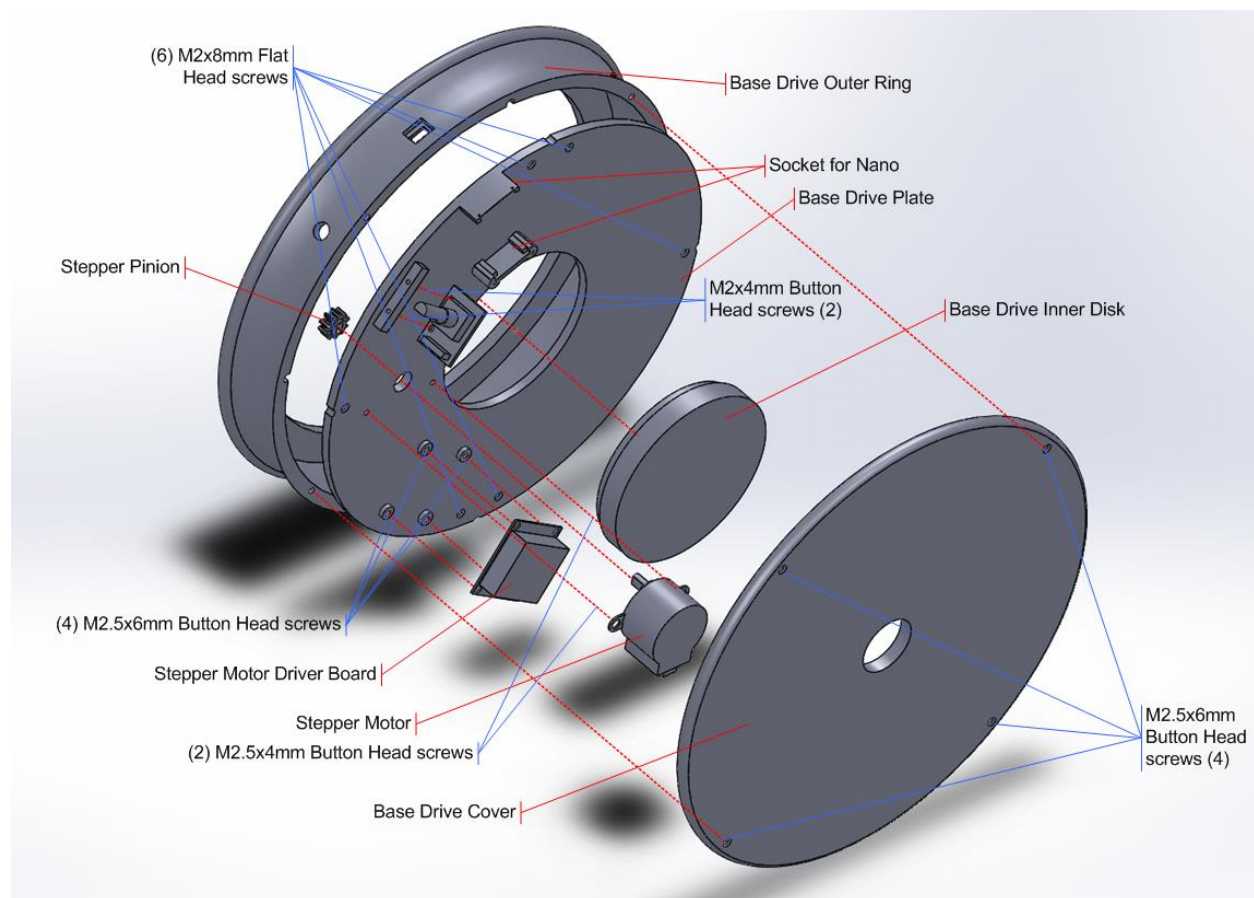
After attaching the stepper motor to the Base Body, press on the Stepper Pulley.

4 Final Assembly

Press a MR128 ball bearing into the *L3 Frame Support*, then slide the *L3 Frame Support* onto the L2 Assembly *L2 Lower Body* shaft with the hex end. Press the *L2 T25 M2 3mm Gear* onto the hex end of the shaft and through a *Screw 12mm w screw hole* part, use a M2x8mm flat head screw to attach the gear to the L2 Assembly.

Slide the other L2 Assembly *L2 Lower Body* shaft into the L3 Crown Gear and use two M2x12mm flat head screws to attach the *L3 Frame Support* to the *L3 Frame* of the L3 Assembly.

To combine the Base and L3 Assemblies, I held the L3 Assembly upside down, laid a *L3 Bearing Race Guide* on top of the *L3 Bearing Race Upper* part, inserted the eight 6mm balls. Then laid the *L3 Bearing Race Inner* of the Base Assembly on top of it, and repeated the process of laying down the remaining *L3 Bearing Race Guide* on top of the *L3 Bearing Race Inner* part, inserted the eight 6mm balls, and used eight 2Mx8mm flat head screws to hold everything together.

Now check that the L3 Assembly rotates freely in the Base Assembly. If it binds at some point, it may be due to a gap between the *L3 Bearing Race Upper* part and the *L3 Frame*, as discussed above. You can back off the screws a bit if the L3 assembly binds as it turns.

Screw the Base Drive Assembly to the Base Assembly using four M2x12mm flat head screws. You may have to run a 4mm drill *backwards* down the hole, so that the screws drop in the holes freely.

Finally use four M2.5x6mm button head screws to attach the *Base Drive Cover* to the *Base Drive Outer Ring*.

5   The Stepper Motor

The stepper is a 28BYJ-48. It is a very low cost motor that is used in 1,000,000's of products.

Here is the wiring that I used. The source that I used for the rotary encoder, stepper, and the driver board is below.

Figure 8: Schematics
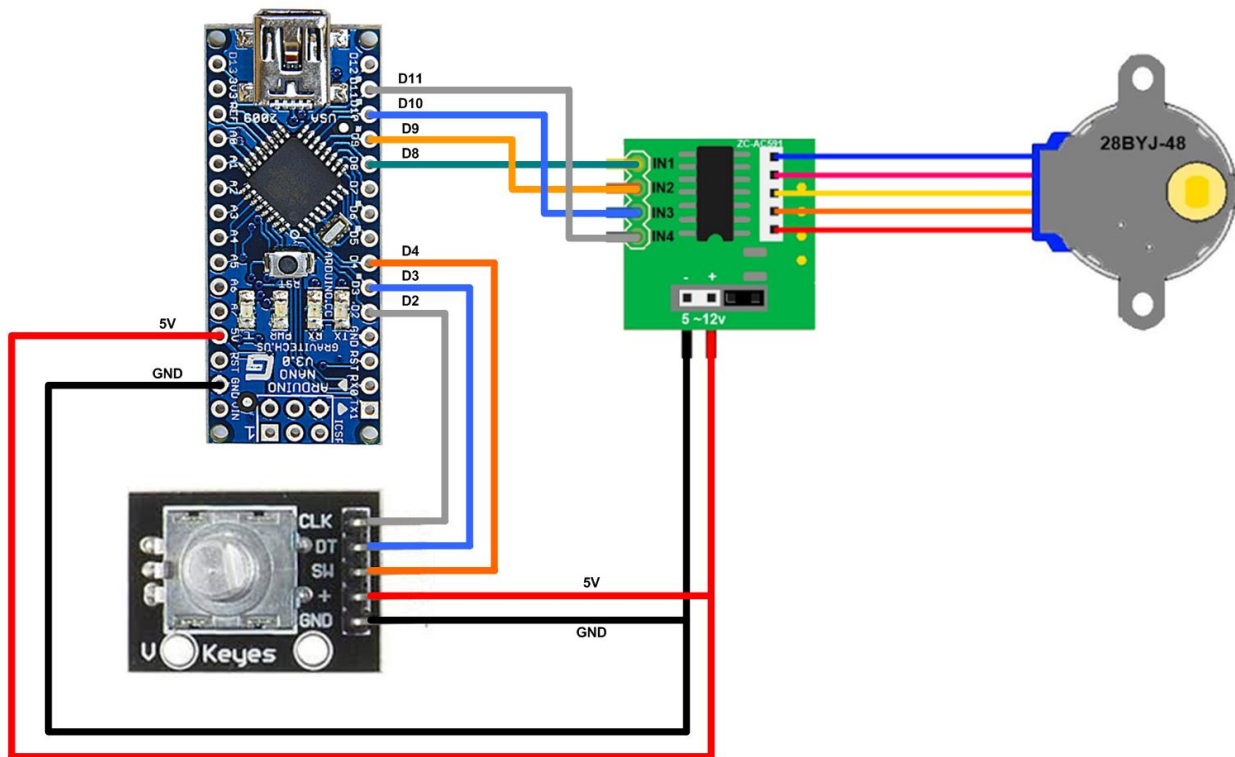
I used the stepper_encoder.ino sketch files, originally from https://dronebotworkshop.com, and modified by RUZICK to incorporate the rotary encoder.

With the stepper_encoder.ino code loaded the stepper starts turning at the last speed setting as soon as you plug in the USB cable.

The USB ports on my laptop couldn't source enough power when the stepper driver power wires were connected to the Nano, and it wouldn't boot. In this case, I attached a separate 5V supply to the stepper driver board. You may need to attach your computer through powered USB hub.

6 Sources

For the screws I used ones that I had left over from previous projects. So I don't have any screw sources that I specifically used for this project. I started off with assortments of 2 and 2.5 mm (4 to 10 mm long), flat head, button head, and hex Socket Head Cap screws and had to order another 100 from ebay, when I get low on a particular size.

From the following ebay page, you can order 2 or 2M, black or steel, cap, button or flat head screws in 4-30mm lengths for under $2 for 50. If you search, you will find a similar page for 2.5M screws.

https://www.ebay.com/itm/50X-M2-M3-M4-M5-Hex-Socket-Allen-Head-Screw-Bolt-Self-locking-Nylock-Nut-Locknut-/162286993963?var=&hash=item25c90f022b

Below are the links to some of the parts that I did order for this project.

Nano Board

https://www.amazon.com/ATmega328P-Microcontroller-Board-Cable-Arduino/dp/B00NLAMS9C/ref=sr_1_13?crid=35OM3460R5IPV&keywords=nano+arduino&qid=1566284205&s=gateway&sprefix=Nano+Ard%2Caps%2C208&sr=8-13

Kit of 5 28BYJ-48 steppers and driver boards for $12.50. They were cheap, and now I have plenty for future projects.

https://www.amazon.com/gp/product/B076KDFSGT/ref=ppx_yo_dt_b_asin_title_o04_s00?ie=UTF8&psc=1

Maxmoral 2pcs Rotary Encoder Module KY-040 360 Degrees for Arduino Compatible Brick Sensor Switch Development Board

https://www.amazon.com/Maxmoral-Encoder-Degrees-Compatible-Development/dp/B07M631J1Q/ref=sr_1_13?crid=KSJ7Y7TJBM9X&keywords=arduino+rotary+encoder&qid=1566284441&s=gateway&sprefix=Arduino+rotary+e%2Caps%2C201&sr=8-13

HATCHBOX PLA 3D Printer Filament, Dimensional Accuracy +/- 0.03 mm, 1 kg Spool, 1.75 mm, Transparent Red

https://www.amazon.com/gp/product/B00M0CS68E/ref=ppx_yo_dt_b_asin_title_o05_s00?ie=UTF8&psc=1

2x5x2.5mm MR52-ZZ Precision Ball Bearings Chrome Steel, Metal Shield

https://www.amazon.com/gp/product/B00TVPSCVO/ref=ppx_yo_dt_b_asin_title_o06_s00?ie=UTF8&psc=1

20x27x4 Metal Shielded Bearing 6704-ZZ

https://www.amazon.com/gp/product/B00LN41BNW/ref=ppx_yo_dt_b_asin_title_o05_s00?ie=UTF8&psc=1

uxcell 10pcs MR128ZZ 8mmx12mmx3.5mm Double Shielded Miniature Deep Groove Ball Bearing

https://www.amazon.com/gp/product/B075CMJT1X/ref=ppx_yo_dt_b_asin_title_o05_s00?ie=UTF8&psc=1

Atoplee 4pcs Miniature Axial Ball Thrust Bearings F8-14M (8x14x5mm)

https://www.amazon.com/gp/product/B01EMZ24G6/ref=ppx_yo_dt_b_search_asin_title?ie=UTF8&psc=1

6mm (0.236") Precision Chrome Steel Bearing Balls G25

https://www.amazon.com/PGN-0-236-Precision-Chrome-Bearing/dp/B07DKSN46T/ref=sr_1_2_sspa?keywords=6mm+ball+bearing&qid=1557296488&s=gateway&sr=8-2-spons&psc=1

7   Escape Wheel

The trick to aligning the balance spring is to position the balance wheel so the Balance Wheel Post, that engages with the Fork Pins, is pointing directly at the center of the Fork shaft. I refer to this position as the 'natural center position' of the Balance Wheel. And the Fork Center Pin should be pointing directly at the center of the Balance Wheel Shaft. See Figure 9.

Then, with the Balance Spring rotated to the position where it drops into the Balance Spring Adjuster mount on the L1 Frame 3, push the hex center of the Balance Spring onto the hex of the Balance Wheel. Then push the hex center of the Balance Wheel onto the hex of the Balance Shaft Note, you may have to file the hex's before you start to make this a snug slip fit. I didn't glue the Balance Shaft or the Balance Spring to the Balance Wheel, because the Balance Spring is the part most likely to fail, and I wanted to be able to easily replace it.

When I was testing my L1 Assembly, the Balance Wheel was regularly hanging at the same angle. Using the L1 Balance Spring Adjuster to rotate the Balance Spring so that the 'natural center position' of the Balance was better aligned with the Fork shaft, and it made the problem go away.

After connecting the balance spring to the balance wheel and the tourbillon frame, the balance wheel tab should point directly at the fork, when the balance wheel is at rest. See Figure 9.

It doesn't really matter what angle the Balance wheel is at, relative to the *L1 Balance Spring* and the *L1 Balance Shaft*. But the *L1 Balance Spring* to *L1 Balance Shaft* relationship is critical.

Figure 9: Balance Wheel to Fork Alignment
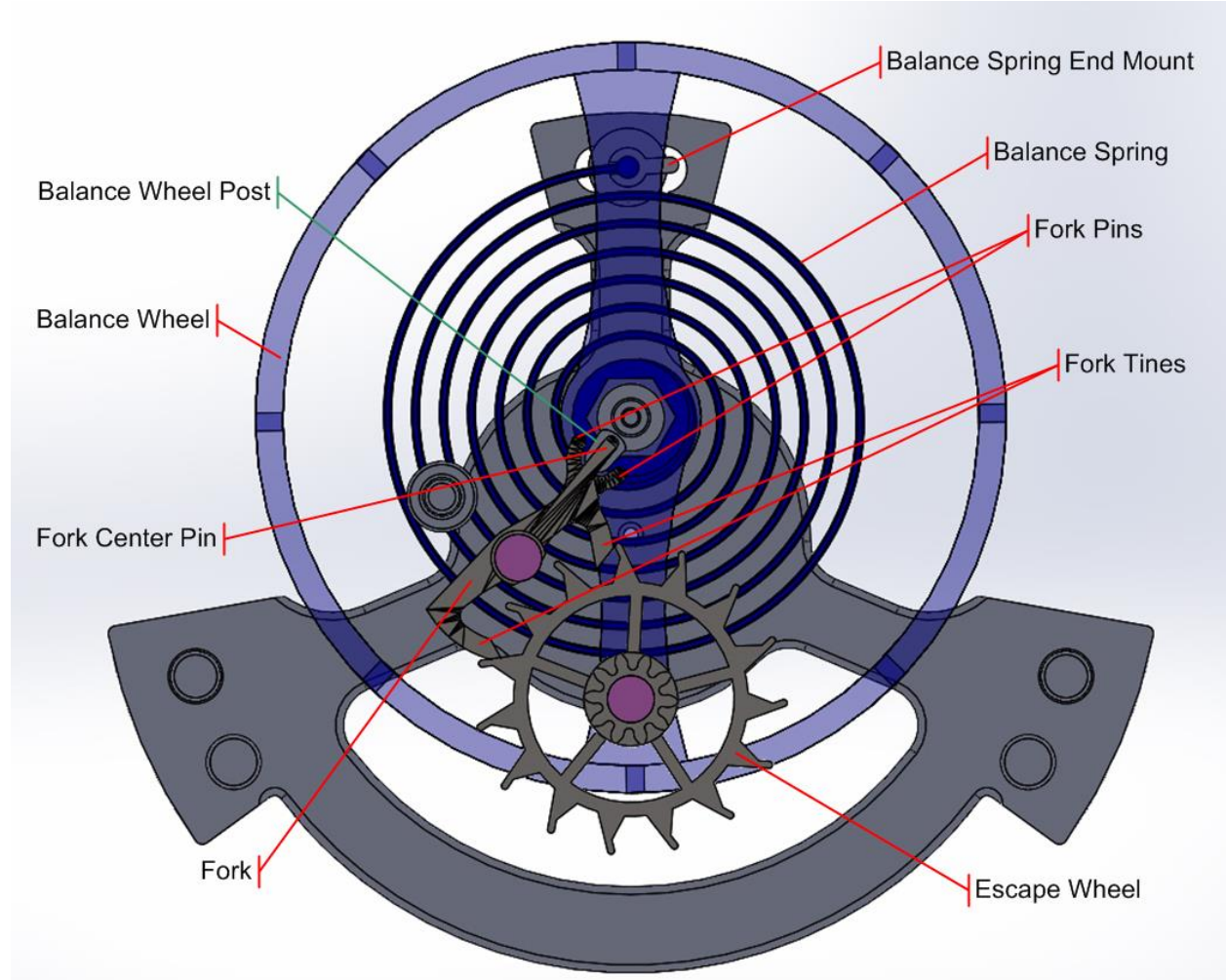
Note: The *Balance Wheel* is 'transparent' in the drawing to allow the *Balance Spring End Mount* to be visible.

7.1   Getting it to Tick

This is the most critical part of the design. It is made easier if you have printer that generates accurate prints. With my printer, I needed to drill out the all parts so the shafts spun freely, but I did not need to file any of the parts.

There are 4 parts involved, the Balance Wheel, the Balance Wheel Spring, the Fork, and the Escape Wheel. The names in this section refer to Figure 9.

- Make sure that any surfaces that contact between the Balance Wheel, Fork, and Escape Wheel are free of burrs, bumps, or any other printing artifacts that may cause a surface not to be smooth. If not, then some filing or scraping with a knife may be necessary to smooth the parts.

- Make sure that the Balance Wheel, Fork, and Escape Wheel each rotate freely when installed by themselves. The Wheels should spin easily, and the Fork should flop back and forth as the

assembly is rotated.

I ran a 2.5mm drill through the Fork and Escape Wheel shaft holes, and a 3.5mm drill through the Escape Wheel shaft hole to ensure that any printing artifacts were cleared out of the cavities.

- Note: Run the drill backwards in plastic at first, otherwise it may auger in at some weird angle and ruin the part. Once the drill is running smoothly backwards, reverse it to clear out the plastic shards.

- All bearings need to fully seated, so that their top surface is flush with the respective part. You may need to pop them out and scratch out underneath them with a knife.

- With just the Fork and Escape Wheel installed:

    - Turning the Escape Wheel backwards (clockwise in Figure 9), should cause the Fork to snap back and forth easily.

    - And turning it counterclockwise should cause it snag against a Fork Tine. If the Fork snaps back and forth a little, it is OK. But if it never snags the Balance wheel when rotated counterclockwise, then the Fork Tines may be too short.

- With just the Balance Wheel and Fork installed (No balance Spring), spinning the Balance Wheel back and forth should cleanly engage the Fork. If there is any sign of a snag, or slowing down, then inspect where the two parts are rubbing, and file the offending part lightly. It is easy to take off too much. If you do, just print another part, and start again.

- Depending on the direction the Balance Wheel is spinning, one of the Fork Pins and the Fork Center Pin should slide along the surface of the Balance Wheel shaft, but not touch so much that they slow the Balance Wheel down. The two contact points formed by the Fork Pin and the Fork Center Pin act to hold the Fork at an angle where its Tines can snag/block an Escape Wheel tooth.

    - When the Balance wheel is rotated in the opposite direction, the Balance Spring Post engages with the Fork Pins to swing the Fork in to its opposite position. The swinging action of the Fork causes the Escape Wheel to advance one tooth, and engage with the opposite Fork Tine.

    - If there is any binding when the Fork swings, you will need to file the Center Pin a little shorter.

- When all the parts are assembled, a *very light amount of torque* on the Escape Wheel in the counterclockwise direction should cause the fork to swing, and the Balance wheel to rotate. Continuing to put torque on the Escape Wheel will cause the Fork to move to its opposite position when the Balance Wheel swings back, due to the Balance Spring. As long as you put consistent, light torque on the Escape Wheel, the assembly should continue to tick.

8 STL Files

Unless noted, I used a .2mm first layer and all other layers were 1.5mm.

I also set the Perimeter Vertical Shell count to 3. I used the default settings for all the support options.

Sub-Assy	File Name	Quan.	Support material	Color	Notes
Base	Base Drive Cover	1	No	black	
	Base Drive Inner Disk	1	No	black	
	Base Drive Outer Ring a	1	Yes	black	Split *Base Drive Outer Ring* into 2 parts because it didn't fit on my print bed.
	Base Drive Outer Ring b	1	No	black	
	Base Drive Outer Ring	0	Yes	black	
	Base Drive Plate	1	No	black	
	Base Drive	0	Yes	black	
L1	L1 Balance Shaft 2	0	Yes	silver	Optional L1 Balance Shafs. Only use one.
	L1 Balance Shaft 3	0	Yes	silver	
	L1 Balance Shaft	1	Yes	silver	
	L1 Balance Spacer	1	No	silver	
	L1 Balance Spring End Mount	1	No	silver	
	L1 Balance Spring	1	No	silver	
	L1 Balance Wheel	1	No	copper	
	L1 Bearing Spacer Lower	1	No	any	
	L1 Bearing Spacer Upper	1	No	any	
	L1 Escape Wheel	1	No	silver	
	L1 Fork 2	0	Yes	silver	Optional L1 Forks. Only use one.
	L1 Fork 3	0	Yes	silver	
	L1 Fork	1	Yes	silver	
	L1 Frame Base Alignment Pin	2	No	silver	
	L1 Frame Base Bridge Inner	1	Yes	silver	
	L1 Frame Base Bridge Main	1	Yes	silver	
	L1 Frame Base	1	No	silver	
	Jewel 6mm	3	No	Red Transparent	Set layer height as low as possible.
L2	L3 Bearing Holder	1	No	silver	
	L2 Cap Screw	1	No	silver	
	L2 Counter Weight Cap	1	No	any	
	L2 Crown Bearing Washer	1	No	any	
	L2 Drive Gear	1	No	silver	
	L2 Lower Body Trellis	1	No	gold	
	L2 Lower Body	1	Yes	gold	
	L2 Shaft Spacer	1	No	any	
	L2 T25 M2 3mm Gear	1	No	silver	
	L2 Thrust Bearing Washer	1	No	any	

Sub-Assy	File Name	Quan.	Support material	Color	Notes
	L2 Torque Spring Washer	1	No	silver	
	L2 Torque Spring	1	No	copper	
	L2 Upper Body Loading Plate Lower	1	No	silver	
	L2 Upper Body Loading Plate Pin	1	No	copper	
	L2 Upper Body Loading Plate Upper	1	No	silver	
	L2 Upper Body	1	Yes	gold	
	Jewel 11mm	1	No	Red Transparent	Set layer height as low as possible.
L3	L3 Bearing Race Guide	2	No	any	
	L3 Bearing Race Inner a	1	No	any	Allow printing the *L3 Bearing Race Inner* without supports.
	L3 Bearing Race Inner b	1	No	any	
	L3 Bearing Race Inner	0	Yes	any	
	L3 Bearing Race Lower	1	No	any	
	L3 Bearing Race Upper	1	No	any	
	L3 Crown Gear a	1	No	copper	
	L3 Crown Gear b	1	No	copper	
	L3 Crown Gear	1	Yes	copper	
	L3 Frame Ring Gear	1	Yes	copper	
	L3 Frame Support	1	Yes	copper	
	L3 Frame	1	Yes	copper	
	Stepper Pinon	1	No	any	
Screws	Screw 7mm End Cap	8	No	silver	
	Screw 9mm Seat	3	No	silver	
	Screw 9mm Seat w screw hole	1	No	silver	
	Screw 12mm Seat w screw hole	1	No	silver	
	Screw 12mm	8	No	silver	
	Screw 20mm	1	No	silver	
Other	2x1mm Bearing Spacer	5	No	silver	

9   Other Stuff

9.1   Some notes on gluing PLA…

I purchased the Bottle Applicator and Acrylic Cement (also called 'Acrylic Solvent') from Tap Plastics.

Bottle Applicator:
https://www.tapplastics.com/product/supplies_tools/plastic_tools_supplies/hypo_type_solvent_cement_applicator/409

Acrylic Cement:

https://www.tapplastics.com/product/repair_products/plastic_adhesives/tap_acrylic_cement/130

The web page says that the Acrylic Cement is for INDUSTRIAL USE ONLY. This is because it is made up of Methylene Chloride (75-09-2), Trichloroethylene (79-01-6) and Methyl Methacrylate Monomer (80-62-6). ONLY use in a well ventilated area!!! Not only does it smell bad, but inhaling it can hurt you. So treat it with respect. Fortunately a little of it goes a long way, so the fumes from tiny drops are minimal. And don't forget that it is also flammable!

This is probably the most volatile stuff I've ever used. When it comes to evaporation, it makes alcohol look like motor oil. There was an 1/8 inch of it in the bottom of the applicator and it was gone the next day. And this was with the syringe top tightly screwed on, and the cap on it. Also, after 4 months of sitting the garage a 4 oz. container of the stuff that was almost full when I put it on the shelf, was empty! I found that the seal on the container is junk. After tightening as hard as I could, I could tip the container and the stuff would still drip out. My solution, which has worked pretty well, was to store the Cement container in a coffee can with a plastic cap. My theory was that, even with the leaky Cement container, the solvent vapor pressure would equalize inside the coffee can, and slow the evaporation process. But hold the coffee can away from you when you open it, otherwise you will get an eye watering whiff of the stuff.

To fill the Bottle Applicator, just squeeze some air out of it, then stick the syringe into the bottle. It takes a minute, but the stuff will be sucked into the bottle. I found that I never needed very much. An 1/8th of an inch in the bottle, will go a long way. Besides anything you leave in the applicator will evaporate away within a day.

With all this said, a friend said that Acetone was just as effective a cement for PLA. Being a cheapskate, I will try it as soon as my current supply of Acrylic Cement is gone.

Also…

When using this Cement with the Bottle Applicator, its volatility comes into play. Normally you tip the Applicator and give it a squeeze to get a single drop of cement to come out, then relax your grip to cause an additional glue to be sucked back up the syringe. But because this stuff is so volatile, the heat from your fingers causes it to expand, so instead of a single drop, the expansion of the cement inside the bottle causes it to start dripping immediately. Even if you stop squeezing. This will flood your print with glue if the syringe is against it and make a mess. I found the best way to get a single drop was to hold the tip above a piece of cardboard, quickly tilt it to get a drop to come out, then tilt it back immediately, but no so much that the cement reaches the end of the syringe inside the bottle. The 'tilt back' causes

the drop of cement to slide back to the working end of the syringe, without additional drips landing on your work. Note: this only works if there is just a little solvent in the bottle.

10 Release Notes

Date	Notes
8/20/19	Initial release.
10/3/19	Corrected references to the thrust bearing, changing FM8-16 to FM8-14.
11/16/19	Modified screw lengths to prevent stripping them, or punching through parts. Modified Base Drive Cover to accept 2.5mm button screws. Added chamfers to trellis screw holes to accept flat head screws.