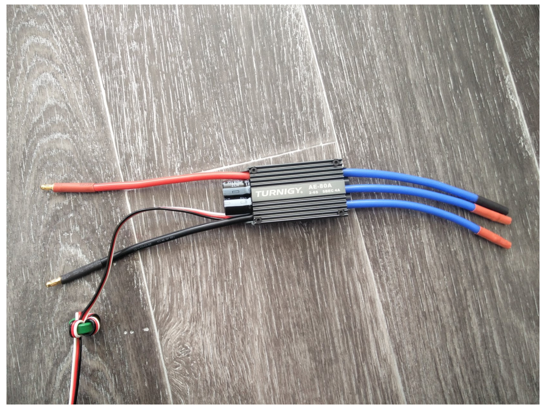
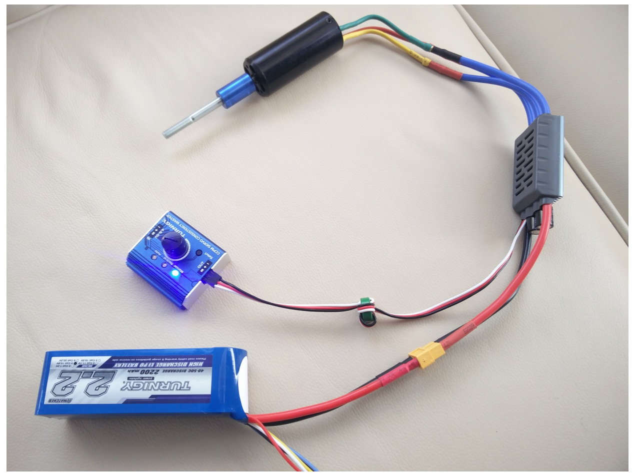
Propulsion Unit Manufacture

Electronic Components Assembly



The ESC's (electronic speed controller) responsibility is controlling the brushless motor as well as "feeding" it with a fixed amount of current. This is a 80A ESC which is the maximum the motor can take, ensuring that the motor will be pushed to output the most torque it can provide without being damaged. With this component, I soldered on 3.5mm bullet connectors and applied heat shrink tubing around these to cover up the exposed metal from the connectors—this is particularly important since 80A could even cause a lethal shock if touched.



This is the completed circuit. It features a 2200mAh 4 cell battery with a voltage of 14.8V. The motor itself can actually take up to 22.8V which would greatly increase the max rpm the motor can achieve. However, high rpm equates to much louder noise which is not desirable for a fan in a home environment so these speeds would not be used and hence not required not to mention that the battery and charger was much cheaper than that for a 6 cell 22.8V battery. The motor itself has been equipped with an aluminium alloy coupling converting from the M4 prop shaft of the motor to the new M6 shaft onto which the impeller will be attached onto. The M6 shaft originally started its life as a regular 60mm bolt but the head was sawed off with a hacksaw for this demonstration. This particular bolt was selected due to its large shank which is a superior surface to screw the grub screw onto.

The image above shows the motor spinning after testing with it. A server tester component with a variable knob is used to control the speed of the brushless motor; this is connected to the circuit via the UBEC cable that branches from the ESC. The servo tester allows me to test the motor at different speeds relatively accurately with much greater ease and reduction of cost compared to using a remote controlled controller.

The original plan was to use a locknut to screw onto the shaft, however, this came with impracticality since removal of the propeller would become slow and lengthy to do. Tightening a locknut would require using one spanner to tighten the bolt whilst using another to keep the shaft still by holding onto a small outcrop of the prop shaft on the other side of the motor. This is difficult to do and the spanner often slips from the shaft. A solution was to make my own propeller nut that has its own grub screw which will ensure that the nut is securely attached whilst being much easier to remove if needed.

Here, I designed the whole propeller nut, featuring a hex base for tightening with a spanner if required as well as a M4 grub screw hole that will take the grub screws that came with the coupling used earlier in this project. For aesthetics and experimentation, I added further detailing to the propeller, creating an interesting appearance - at least it shaves off a little weight. This was manufactured by iMaterialise who specialise in 3D printing. This was 3D printed in wax using the SLA process to create a high resolution wax model; the wax was then investment sand casted with bronze. Although bronze is not an ideal material and aluminium would've made better choice, the casting and SLA processes would result in much better detail, resolution and surface finishing that that of aluminium which has a lower tolerance and a rough powdery surface finish. Another benefit is that due to the fact that bronze has been cast, the material has retained it mechanical properties unlike aluminium from the DMLS process which will be weaker and more prone to microfracturing than regular machined aluminium alloys. Nevertheless, this propeller nut was more of an experiment with metal 3D printing than anything else, especially since I could have obtained an off-

However, the threads for the holes could not be 3D printed due to their fineness and had to be done by hand. The holes themselves were actually designed to be narrower than required so that the thread could be created. The holes were tapped using a M4 and a M6 tap; the above image shows regular bolts of the right size being screwed into the holes to test if they fit properly.

Initial Impeller Test

The original prop shaft was too long for the new propeller nut and as a result, the shaft had to be cut back so that the nut could fit onto it with a little room spare for tightening. The new propeller nut worked successfully, keeping the impeller tight and secure onto the shaft without coming off. Attaching and detaching the prop nut came with a greater level of ease due to only needing to use an allen key to unscrew the grub and the rest can be done by hand - fulfilling the purpose of which this nut was created for.

This test also proved that that the impeller and motor did work with its job of sucking in air and expelling it out. The airflow seemed powerful from the outlet of the impeller despite that it didn't have its housing, allowing the flow to disperse instead of through the ducting. Furthermore, you could feel the suction with your fingers in front of the inlet.

But, this test also revealed that the motor was very loud , even at its lowest working RPM, - it was uncomfortably loud and definitely unideal for a home environment. Nevertheless it's important to remember that the motor purchased was intended for 70mm EDF axial fans for large RC aircraft where outright performance was prioritised over quietness and efficiency in the motor design; these motors are primarily to aid develop designs for the impeller and thus the loudness of the motor itself isn't that relevant. However, efforts will be made to reduce the loudness through techniques researched earlier in the project.

Gauge Test

Here, I wanted to investigate the wobble of the impeller by using a gauge to measure the distance moved by the inlet ring when spinning. This is important to measure so that I can find out how much clearance is required between the housing and the outside of the impeller as well as to ensure that the impeller shaft stays as straight as possible during high RPM to reduce vibrations and noise.

To test this, the motor has to be secured properly and not held in the hand - this issue was addressed by constructing a rig to clamp the motor; the rig was also clamped to the table so that the test isn't ruined by the rig itself vibrating would affect the results. However, I didn't have a way of mounting the gauge since it can't be clamped down and I didn't have a metal surface to attach it into; as a result it had to be held down by hand as best as possible.

After zeroing the gauge as shown by the image above, the motor was revved up to a high speed. It was clear that there was definitely some wobbling which was shown by the needle jumping around. The needle was roughly consistently hitting the point shown in the image, the needle itself is quite blurred and faded but it points to 43 mark. This shows that the impeller wobbles up to 0.43mm from the normal. This is satisfactory and should not cause problems with the impeller wobbling too much.

Vapour Suction Test

Seeing the suction and flow of air visually in reality would require using vapour, smoke or similar. I decided to test using steam since this would be the easiest to produce. Using the testing jig from earlier, steam was from an electric kettle was directed towards the impeller inlet. When spinning, steam started to become sucked into the impeller and be expelled out of the outlet. It was noted that the faster the rpm of the impeller, the further the stream of steam was from the impeller; this shows that the impeller is effective in sucking in air which is majorly important to the functionality of the bladeless fan as a whole.

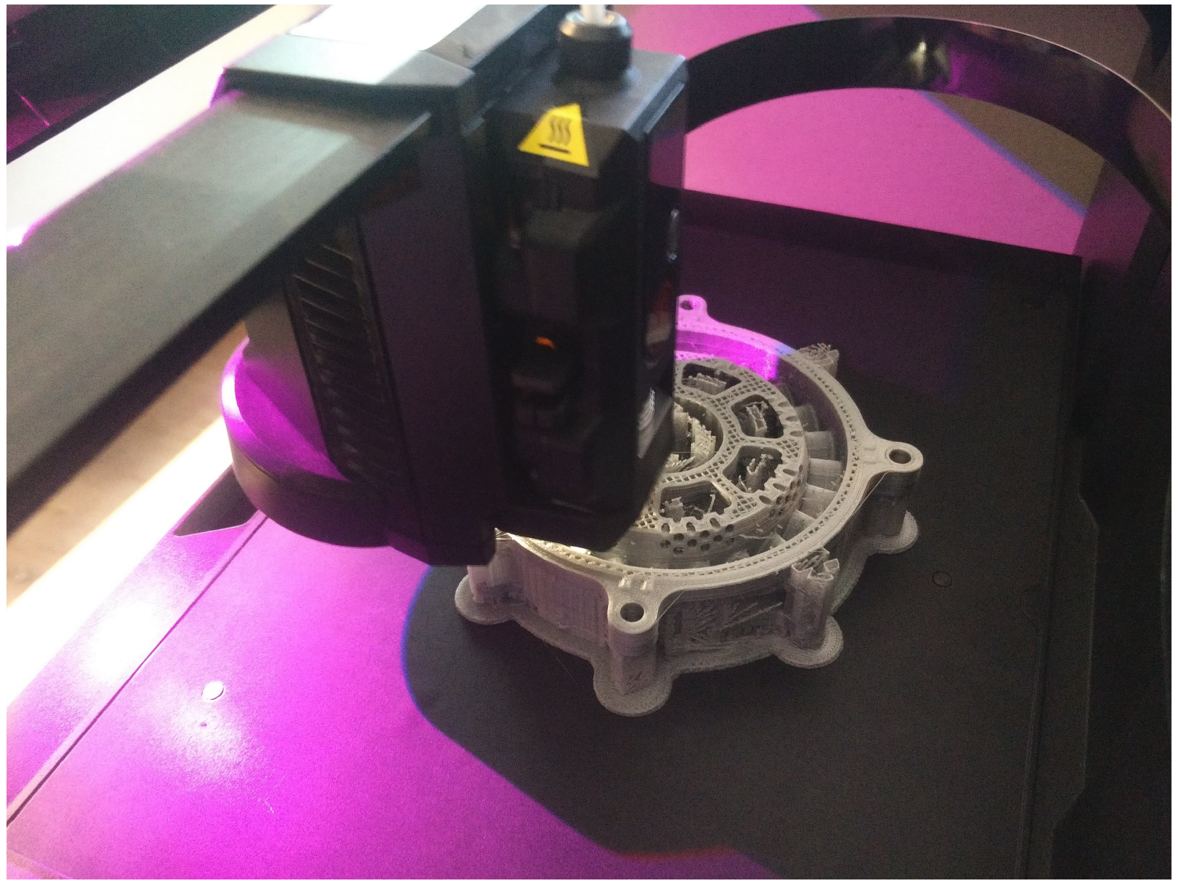
Furthermore, in the outlet, you can see the thin, dense jet of steam exiting the impeller. The photos show that the steam started as relatively large “cloud” of steam beforehand and then is compressed into this tiny steam of gas at the outlet reveals how the impeller is successful in pressuring the steam whilst maintaining airflow.

This test has proven that the mixed flow impeller itself is capable for its application, delivering high pressure airflow and suction. However, the test will not accurately display the fans performance since the ducting design is a major component of how a mixed flow impeller works whilst the suction power itself is unaffected by this and

Prototype Manufacture

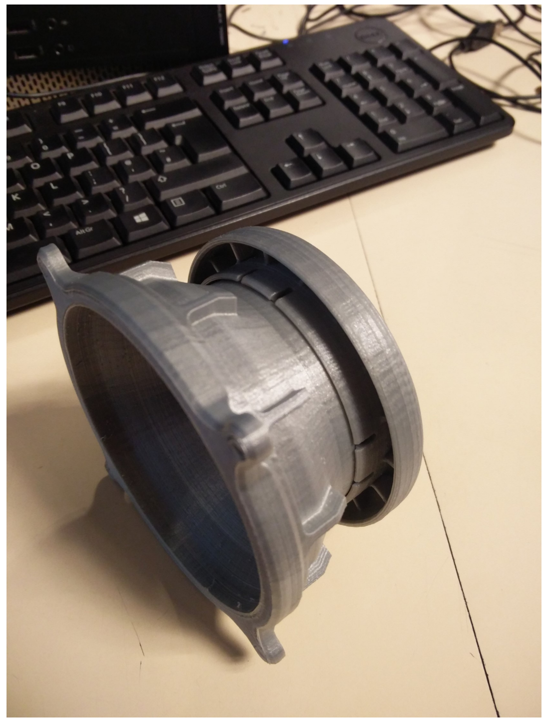
After finalizing the designs and adjusting the propulsion unit components for 3D printing processes and to the motor, the parts were 3D printed using a FDM printer. Some of the main changes include the use of a clamp instead of screws to secure the motor and joining the motor mount and the diffuser as one part to reduce the number of parts, reduce fastening parts and also to free up more space for more blades in the 1st set of stator blades. 3D printing was the obvious choice for the main method of manufacture since these components are too complex to be made by hand; furthermore it would be more “realistic” replication of the final product since it would be using a polymer material. A 40% diamond infill, fine resolution and thicker walls settings were chosen for the print for superior strength and rigidity - especially as the model features thin walls and this will be essential in dealing with the vibrations of the motor. The parts were printed in such a way to obtain the best possible finish in the product as well as keeping the orientation in mind and taking advantage of strength in the XY directions.

The 3D printing in total took over 60 hours to complete all of the parts required. In post processing, all support and raft material were removed, a knife was used to remove small outcrops of filament and a combination of needle files and wet & dry were used to smooth rough areas where it was needed.

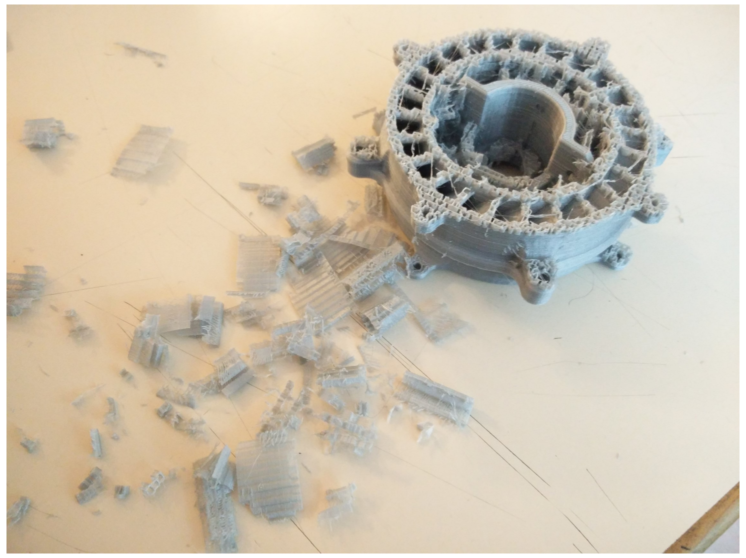


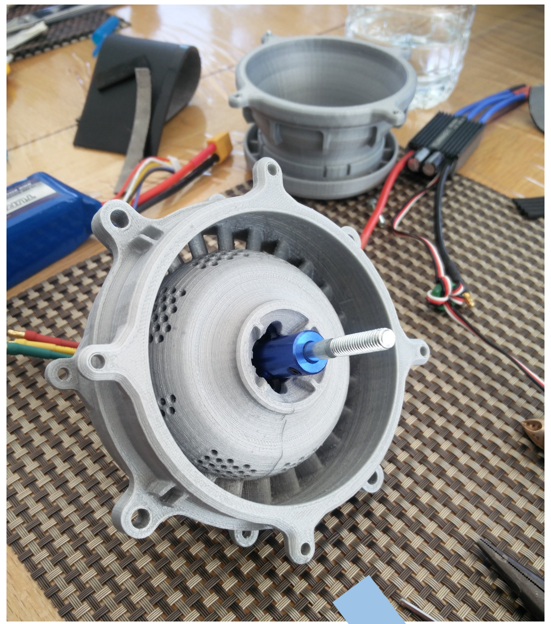
The school’s Makerbot Replicator+ printing out the motor mount. You can see the thick wall thickness and high infill.

Printing time for the motor mount. It took a very long time es-pecially for the size of the component.



This piece had an impres-sive volume of support material. This all had to be removed.

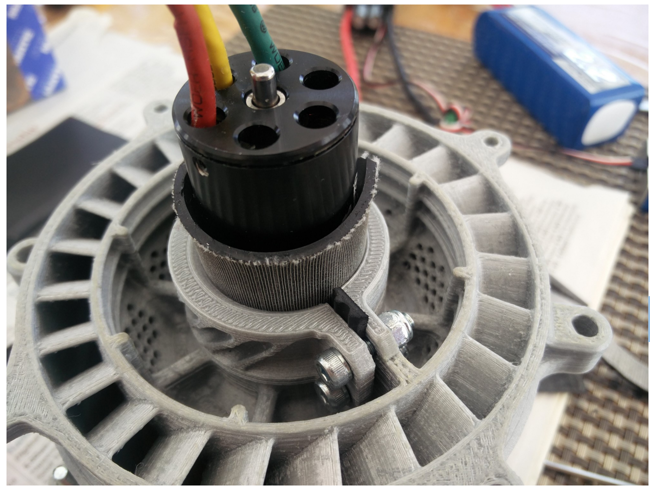




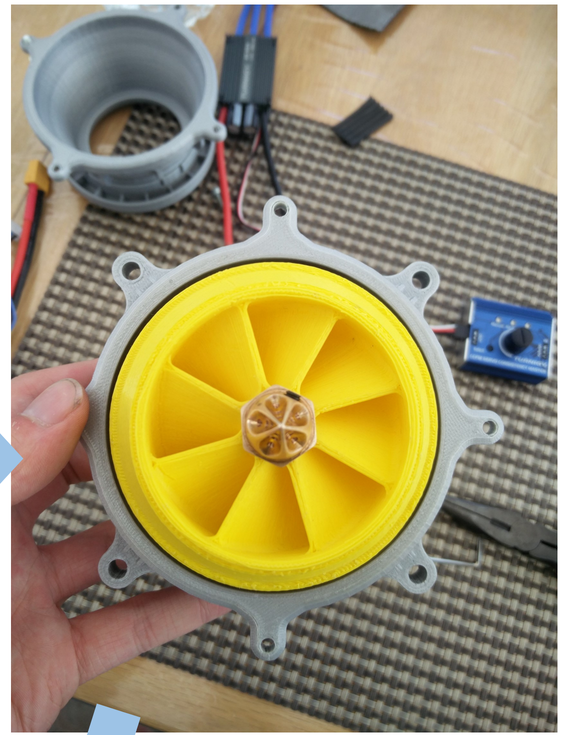
Testing if motor slides in and fits in correctly

A strip of rubber was cut from a Wellington boot—the rubber likely to be neoprene. Silicone or even Sorbothane would've been preferred due to their greater vibration dampening properties but this neoprene piece was much more readily available at no extra cost and the rubber needing to be 2mm thick, the performance gains with the more expensive rubbers is likely to be minimal and hence not worth the delay and cost. The image shows me checking if the rubber piece is the correct size and will fit around the motor properly.

The hex key's short end was cut down so that it could fit inside the mount.

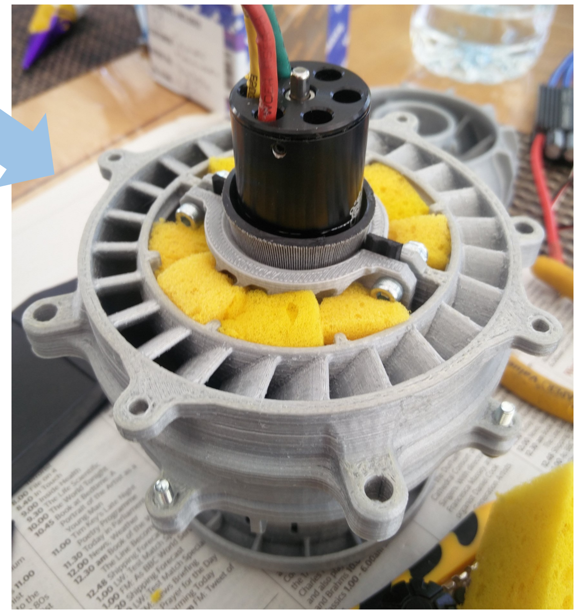


Installing the motor and clamping it down with the bracket. Slightly thicker, ribbed rubber was placed between the gaps of the bracket and the mount to reduce some of the strain. Socket bolts were used since only a hex key could fit in the confined space. Locknuts were also used to prevent the bolts from vibrating loose



The impeller was also attached so I could ensure that the motor & impeller were fully central whilst I was screwing down the bracket's bolts. The image shows the impeller perfectly central and the motor clamped down. The impeller also span freely without any issues.

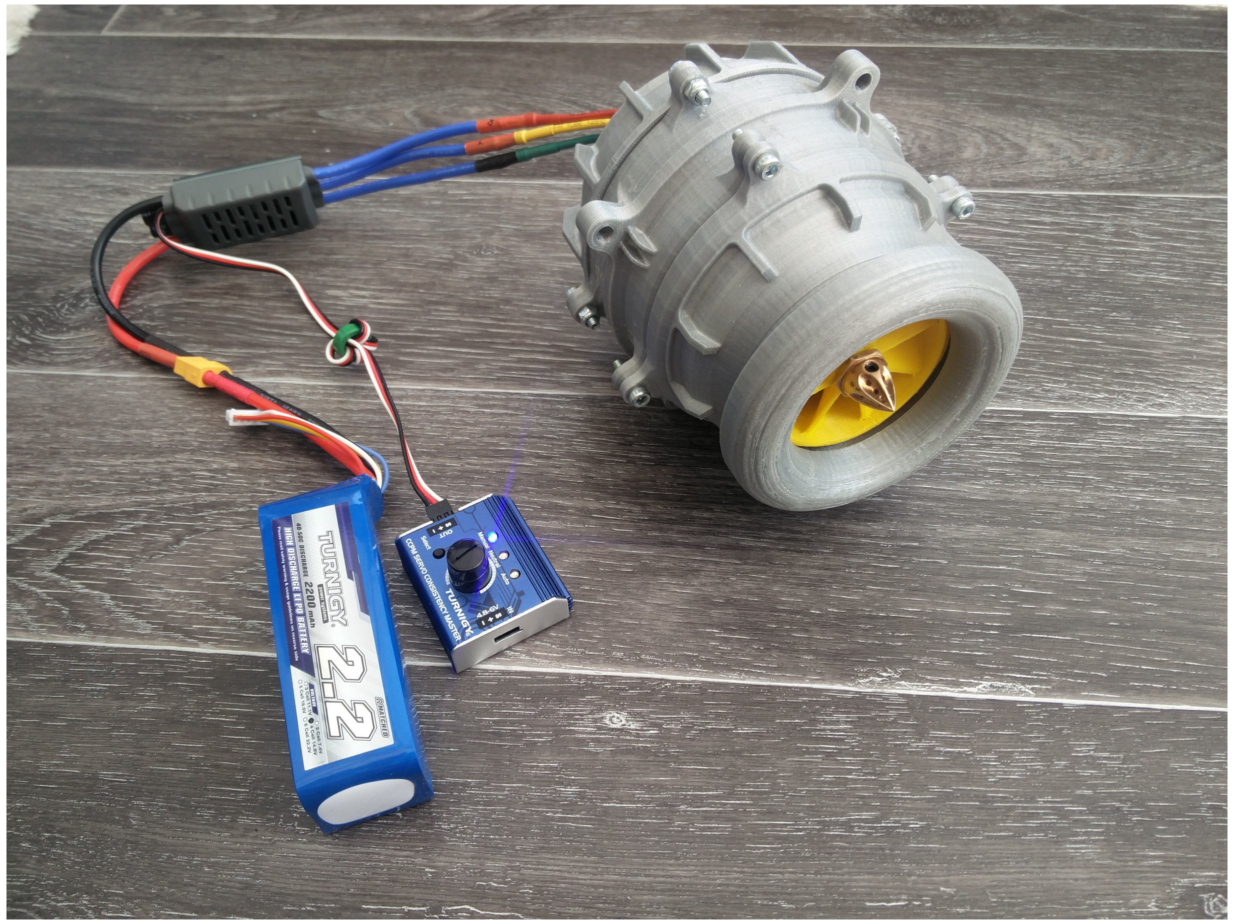
For my version of an acoustic liner to work, sponge has to be added into the inside of the mount so that the holes in the mount are met by sponge. The pieces were all cut from a regular consumer sponge which should do the job due to its open-pore characteristics.

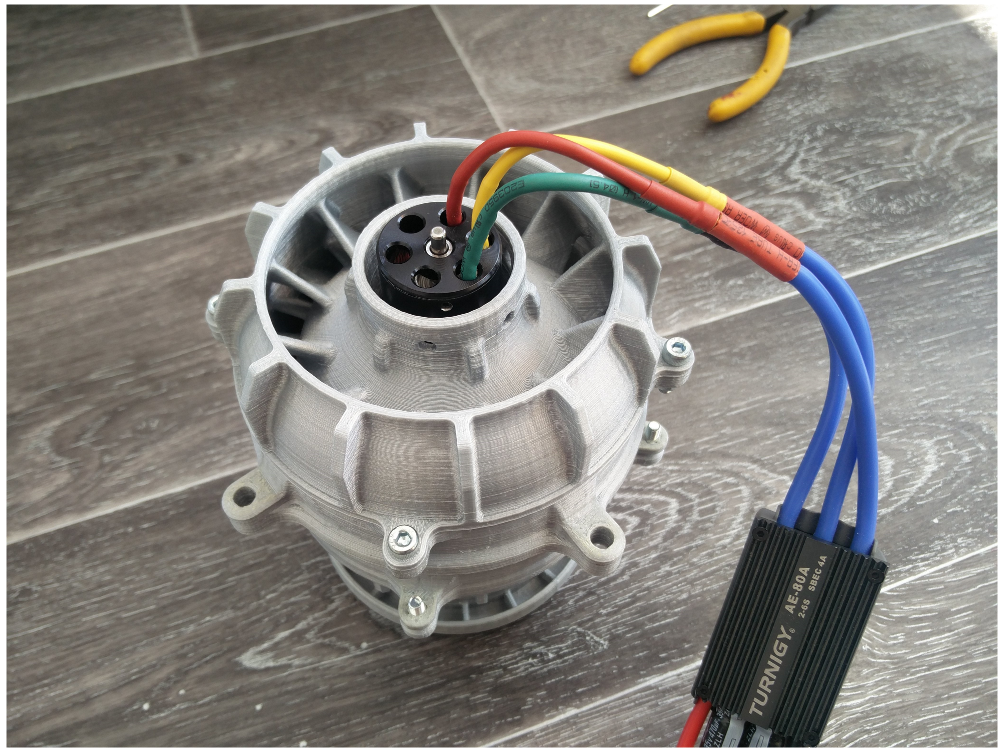


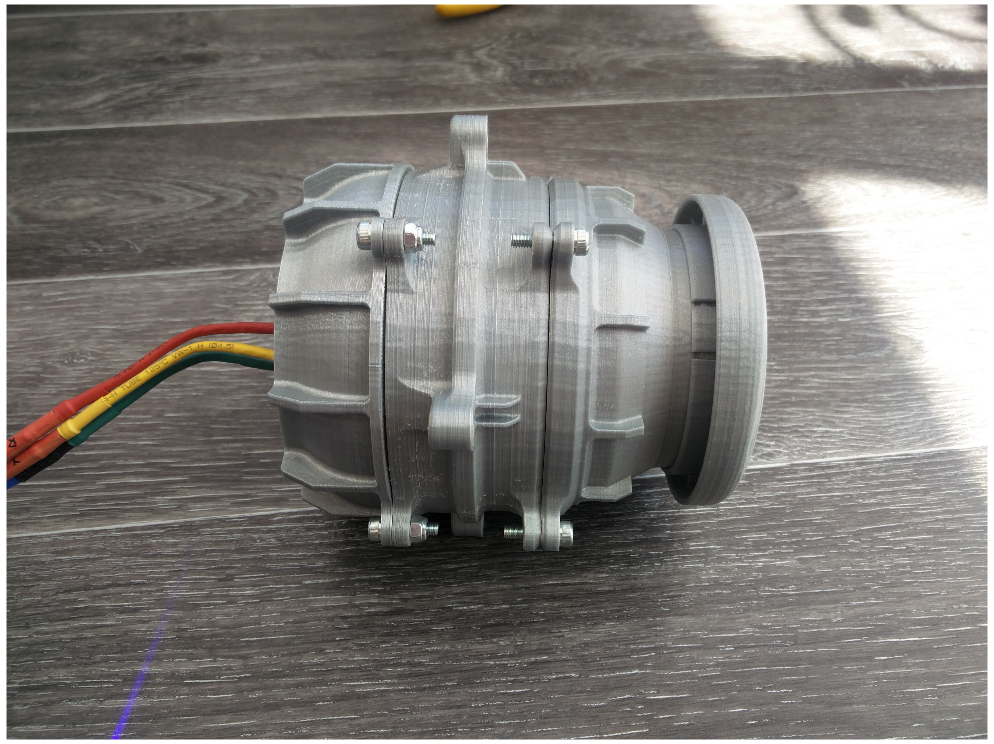
The impeller housing was then attached and again, the impeller was spun by hand as a test to ensure the impeller wasn't catching against the housing. Now that everything on the inside was completed, all what was left to do was to attach the outlet component and screw in all of the bolts and locknuts.

Assembled Prototype

The prototype is now fully assembled with all of the electronic components plugged in allowing for the next stage of testing and iterative development of the impeller design. This is quite a major stage in the project and being able to see my creation now in life was great to see.







Prototype Testing

To test if the prototype works, the motor was spun up and this came with good and bad news. The fan does in fact work, producing high pressure air at the outlet and suction at the inlet. However I do notice that air velocity does drop quite quickly and the range of the blowing air is relatively short. Hopefully, the tight ducting the fan head and the aerofoil design of it should help alleviate this issue.

The prototype also displays a large amount of vibrations and a very loud noise - a noise more associated with power tools than with a quiet fan. At lower speeds the noise could be worked with to be quieter though especially as this whole propulsion unit will be encapsulated with the base and fan head providing muffling for the noise. Either way, this isn't entirely relevant to me at this stage since the whole point of this prototype is not to create a consumer-ready fan but to iterate the design of the impeller to perform better. However, the noise of the propulsion unit is still helpful for me and much can be learned to help prevent noise - but this is to be revisited later.

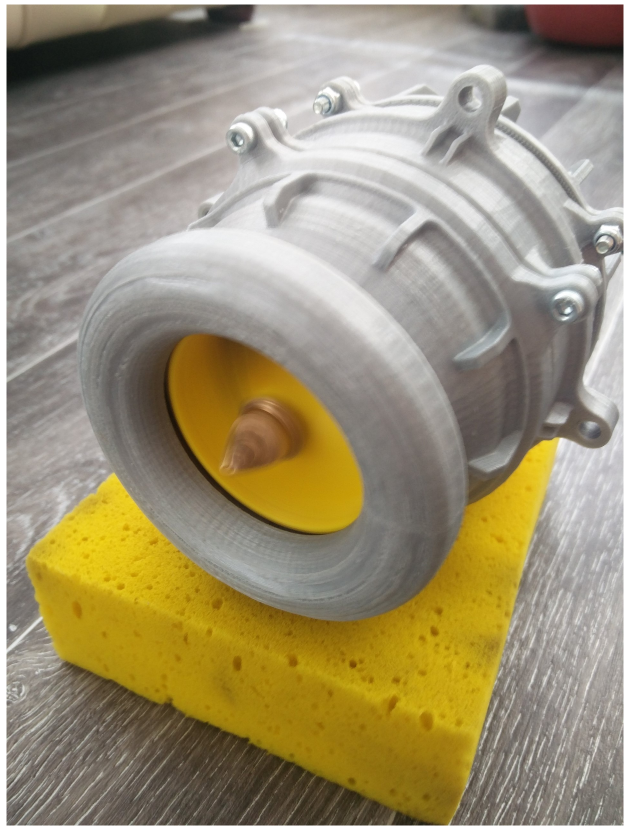
The main issue that I have now found is that the impeller is wobbling excessively and at high speeds the tip of the propeller nut reaches as far as roughly 3mm away from the normal which is not acceptable. This is causing increased vibrations and consequently noise but more importantly it's causing the impeller to skid along the housing preventing me from taking the motor to higher speeds.

There could be several reasons to why this is happening:

1. The propshaft may be bending. This could be happening since the shaft of the motor is only 4mm in diameter - the impeller & coupling is quite large in comparison - and the impeller itself is actually taken quite far out from the motor making it more prone to wobbling especially at high RPMs causing greater centrifugal forces which the M4 shaft may not be able to withstand. This problem, however, would be very difficult to solve without buying a new motor with a larger diameter shaft as well as redesigning other components to accommodate for this.
2. The clamping solution for the motor may not be secure enough. This is possible as I have noticed the motor slip rotationally momentarily upon reaching high RPM. This would mean further tightening the clamp - I would need to be careful not to overtightening since it could bend/break the clamp too much. Even if the clamp was very secure, the rubber lining around the motor may be allowing the motor itself to wobble and vibrate freely at high RPM despite its firmness.

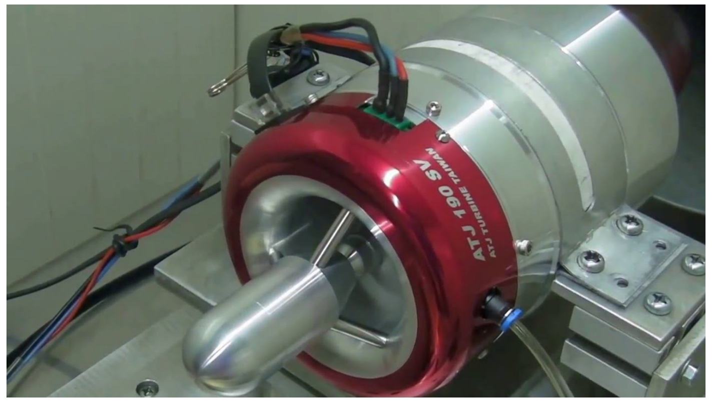
Although reason 1 is relevant, due to the testing with the gauge previously, reason 1 cannot be the main reason to why this issue is arising since the tests showed that the impeller only strayed 0.43mm away from the normal which is far less to what I was seeing now. Whilst it could be a combination of the two reasons, the main reason has got to be reason 2. To help troubleshoot the issue further, I opened up the fan unit and tightened the bracket even further; this stopped the motor from slipping rotationally which is progress but the fan was still wobbling excessively. This can only mean that it's the rubber allowing the motor to vibrate and wobble more freely at higher RPMs.

In attempt to both confirm my conclusion as well as try to solve the issue, I screwed in 3 bolts, equally spaced out, in the holes in the outlet. These holes were designed to allow to use screws to further secure the motor it was really necessarily. When spinning the motor again, I found that the wobbling was definitely reduced by a lot until it got to the point where the vibrations were causing the screws to loosen and hence the impeller wobbling excessively again. This was also shown by the fact that as this happened, a new loud vibrating noise came about due to the motor vibrating against the ends of the screws. So, this shows that my conclusion was correct and that using bolts to secure the end of the motor is probably the best way to prevent the issue. However, I need to find a way of prevent the bolts from vibrating loose and this time I can't just use lock nuts to solve the issue. I decided that I should cut down the bolts to cause less drag to the flow and use superglue to secure these bolts. Hopefully, I should be able to unscrew the bolts if enough force is provided with the hex key if I need to remove them.

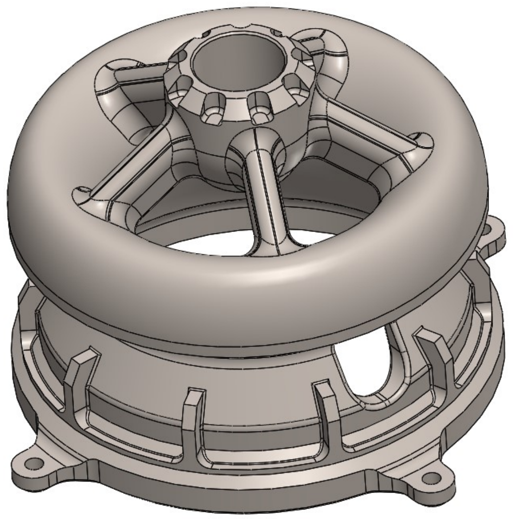


Housing Redesign

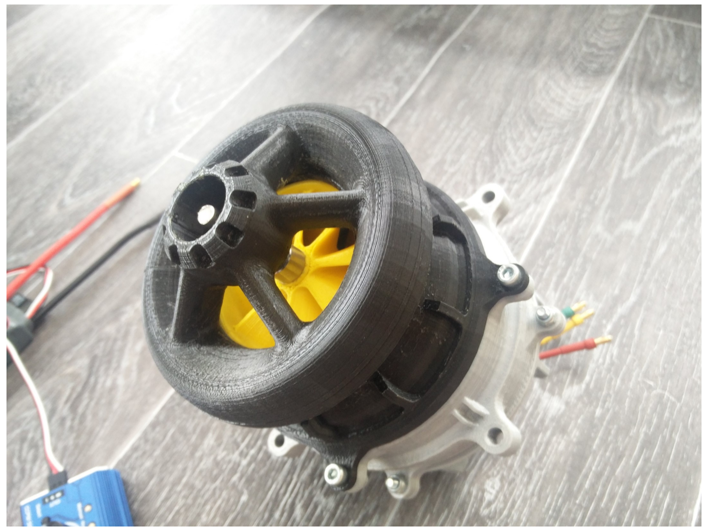
I attempted doing the idea explained in the previous page but I found that due to the weakness of the plastic, I wasn't able to screw in the screws to be tight enough to secure the motor. As a result, that idea had to be scrapped and I had to find another way. I decided to take on the other idea that I had which was to support the other side of the propshaft which would require redesigning the impeller housing to accommodate a bearing to support the shaft - this should prevent the wobbling of the propshaft.

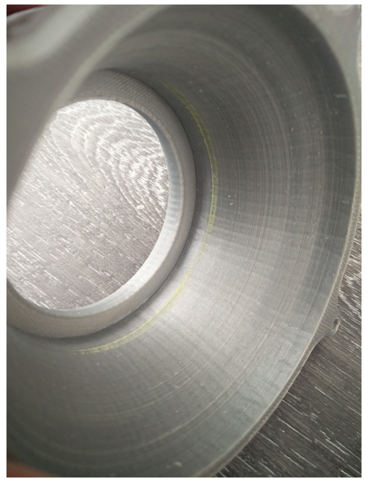


I plan on redesigning the inlet to be similar to this. This is a good model to follow off due to the similarities to my model as well as that it allows sufficient airflow whilst being able to support the propshaft; although, here it's used to contain a starter motor whilst for me, it is just going to house a bearing.



Above is the redesigned impeller housing with the inlet nacelle integrated into it this time unlike before. The central shaft support features a 5 support struts to keep it strong and stable especially under the intense vibrations given out by the motor. The bearing will slot into the hole and then this is plugged with another component and secured with glue. Although this securing method isn't preferable, it is probably the best way without having to use screws which would not perform well when screwing into the PLA plastic. I also added a slot shaped hole onto the side of the housing - this is to allow for the laser tachometer to measure the RPM. I found that it was impossible to get an accurate reading by pointing the laser into the impeller blades since it was giving me readings in the hundreds of thousands or none at all. This is mostly due to the fact that it works best when aimed perpendicular to the rotating cylinder where the surface is non-reflective with a reflective strip so that it can detect the revolutions.





Left: You can see the yellow plastic residue near the inlet where the yellow impeller had scraped along the side.

After 3D printing and some post processing, the bearing was glued into its position. According to the bearing's specification, it has an operating range of up to 52000rpm - higher than motor is able to reach without load. Since a threaded bar cannot be used (due to the bearing), the use of a nut to keep the impeller secure was out of the question and instead an O-ring with a grub screw took its place; a longer smooth 6mm stainless steel rod was used instead of the previous shaft in order to reach the bearing and slot in correctly. This did mean having to press the ring down as hard as possible and tighten the grub so that the impeller wouldn't rotate freely. During testing, the impeller stayed secure and more importantly thanks to the new component, preventing the impeller from being swayed into the side. The side slot also allowed for easy, accurate RPM readings using the tachometer. As a result, it was a great success.

More Testing

Despite that the shaft and impeller were no longer vibrating into the sides of the surrounding part, at high speeds, you could hear a loud sound resembling material being dragged along the inside of the impeller housing, which must've been the tape. Disassembling the device showed the minor damage where the tape had clearly eroded away and black powder had made a mess on the blades— which I found peculiar since the tape was on the outside of the impeller (powder likely to have been sucked in through the open slit between the housing and impeller at the inlet). The only reasonable reason for this is that the tape had started to un-attach itself from the impeller either from the high rotational forces or due to wind starting to catch onto the underside of the tape.

The solution would involve sticking down the tape better to ensure it is properly secured. Use of glues and better performing, clear tape may help too.

Impeller Variations

The new impeller variations were then 3D printed. The following lists the main feature of each impeller variation. The first 4 have the same blade profile with a somewhat shallow outlet blade angle whilst the last 3 are sharper with a higher angle of attack.

<u>Impeller 1:</u> Original yellow impeller with 8 blades

<u>Impeller 2:</u> Same blade profile as impeller 1 but with 5 blades

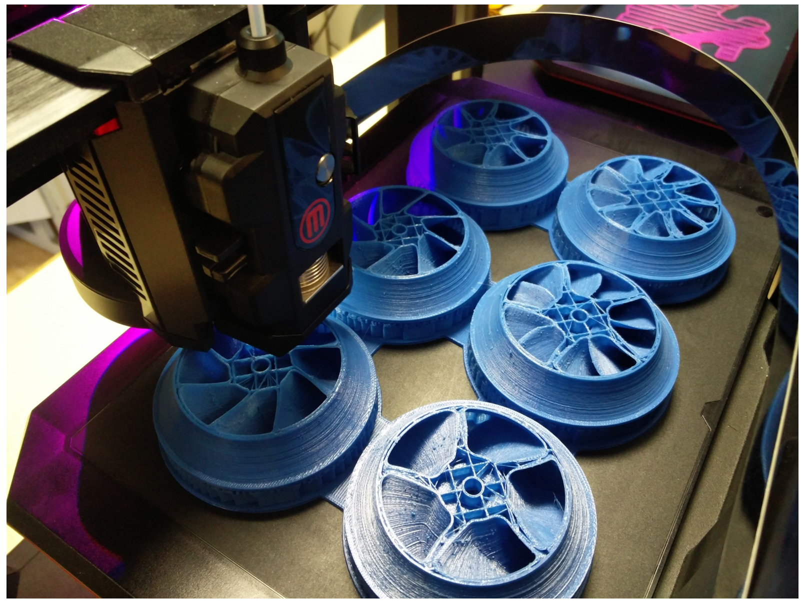
<u>Impeller 3:</u> Contains 10 blades

<u>Impeller 4:</u> 5 main blades but also has 5 splitter blades which are supposed to increase the performance and suction

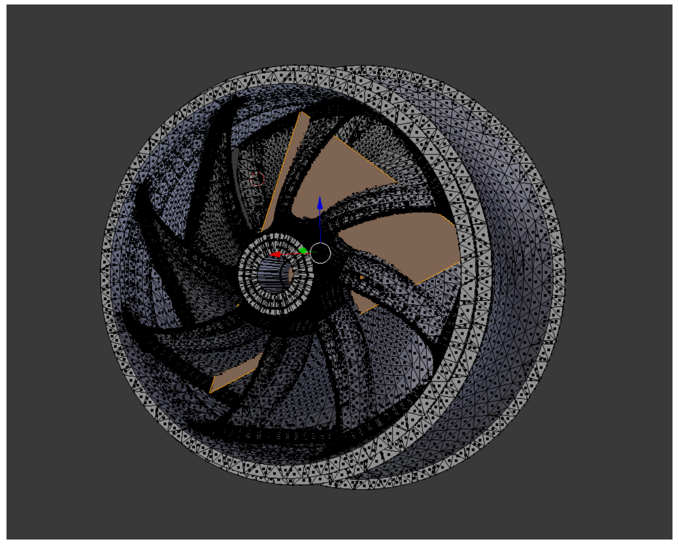
<u>Impeller 5:</u> This takes a new blade profile which has a sharper angle particularly at the outlet. The blade is also thinner allowing for greater air volume within the impeller as well as a slight aerofoil to the blade. 8 blades again.

<u>Impeller 6:</u> 8 blades but this time the blades at the inlet are swept forward. Forward swept blades can improve the pressure curve of the impeller

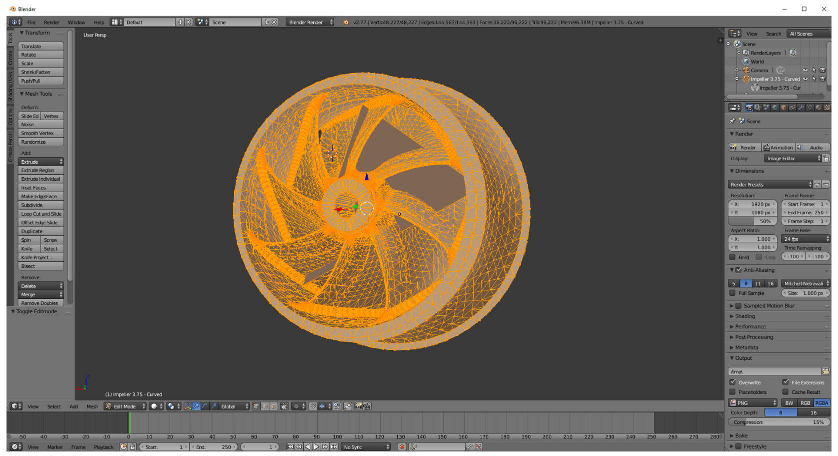
<u>Impeller 7:</u> Same design as impeller 6 but this time the blade is also swept upwards a little—although the root the blade at the centre is lower down.

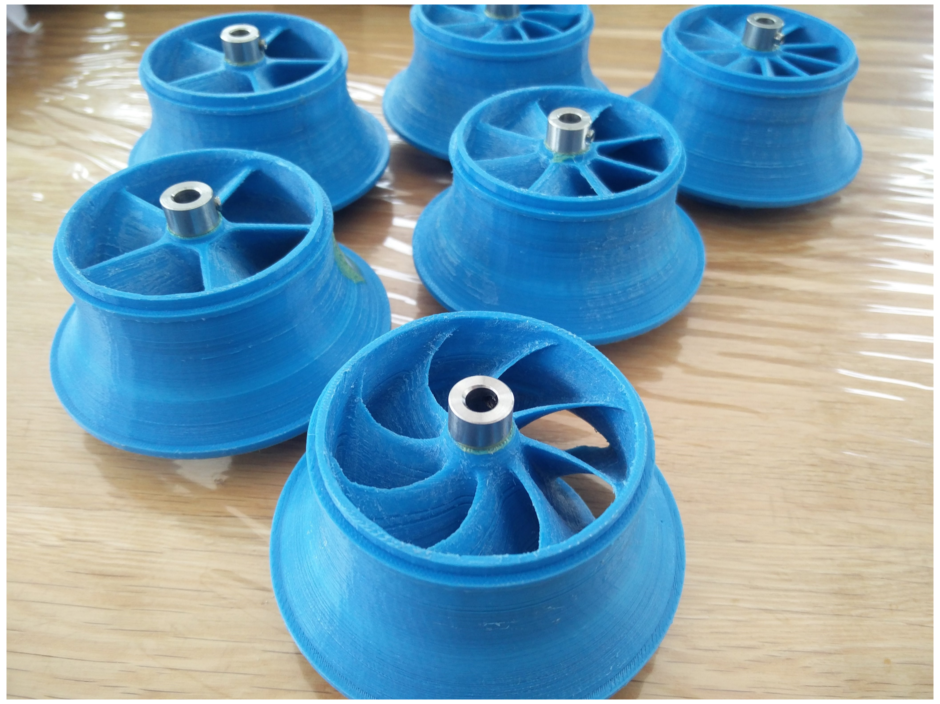


The impellers were all 3D printed in one go taking over 58 hours to print. They impellers needed a lot of cleaning up with bad surface quality on the blades that required sanding and filing. Unlike the first impeller, I had also widened the hole slightly and this time the prop shaft fitted perfectly without needing further drilling.



Many of the exported STL meshes of the impellers featured undesirable artefacts mostly including these stretched around polygons such as the one shown on the left. This could disrupt the 3D printing software or it can assume that that polygon also needs to be printed. So, these need to be cleaned up and removed and the best way to do that is by using 3D software that is based on meshes unlike Solidworks or Autocad. I imported the files into 'Blender' which is a free software with a wide range of tools for game model design, animation and rendering. Blender made it very easy to remove the unwanted polygons by simply selecting them for deletion.

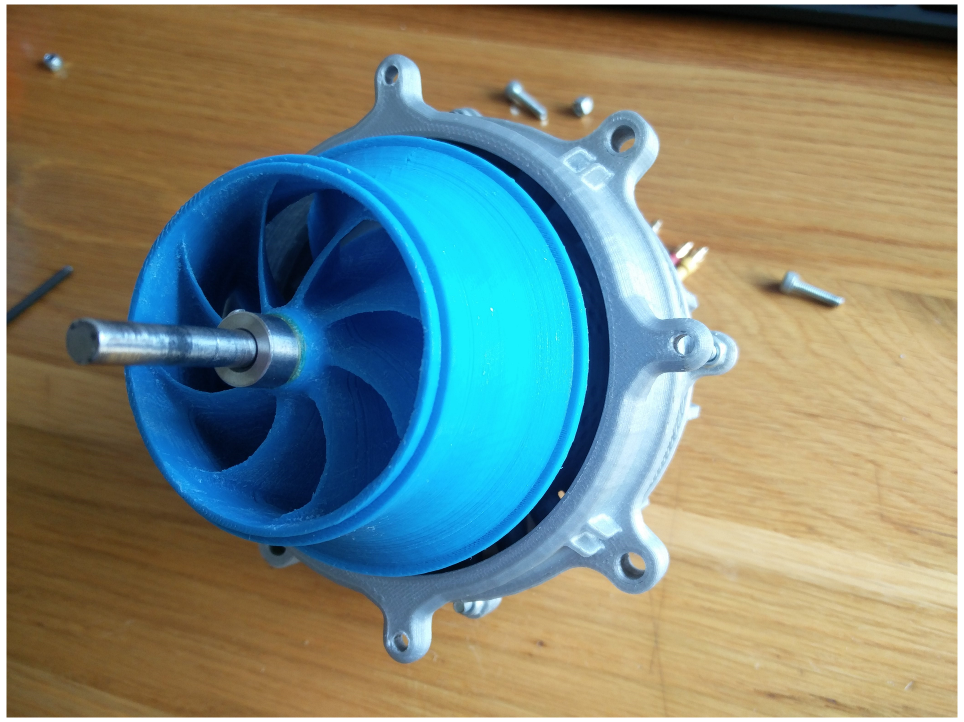




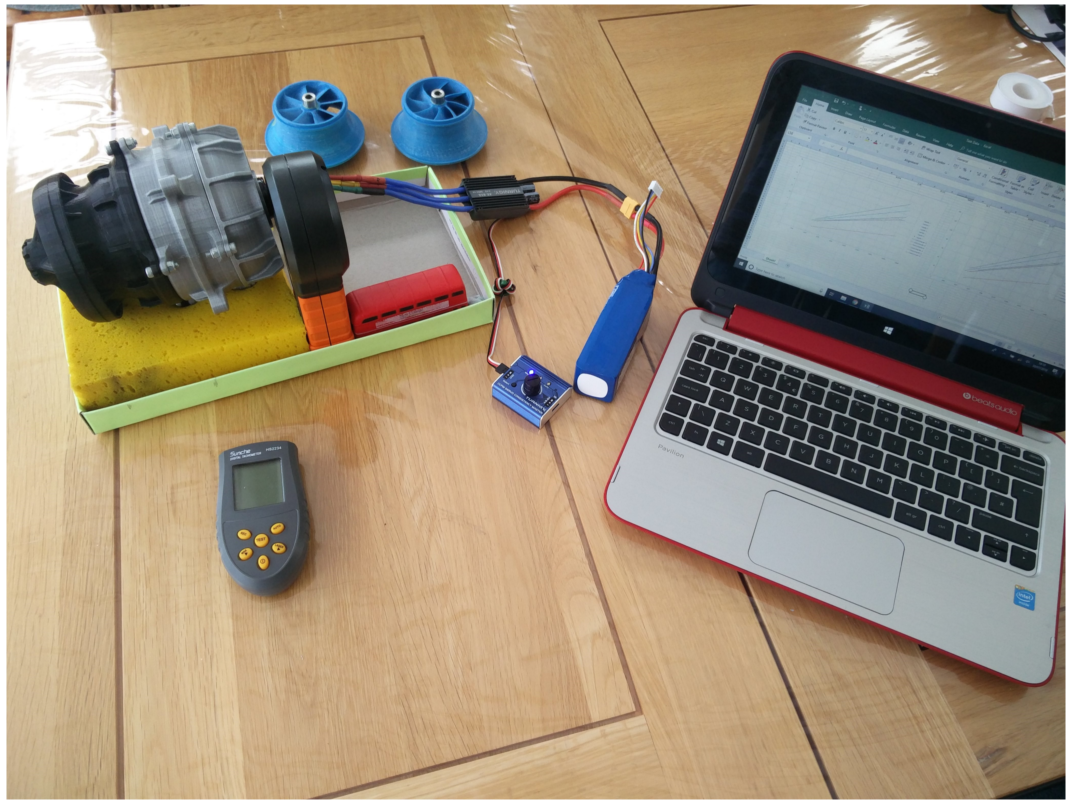
After minor testing, I found as expected, that the smooth locking ring was not able to keep the impeller secure with the shaft having no traction on the impeller ending up where the shaft was spinning much, much faster than the impeller. As a result, more rings had to be obtained but this time they were glued permanently to the impeller, keeping it securing when running.

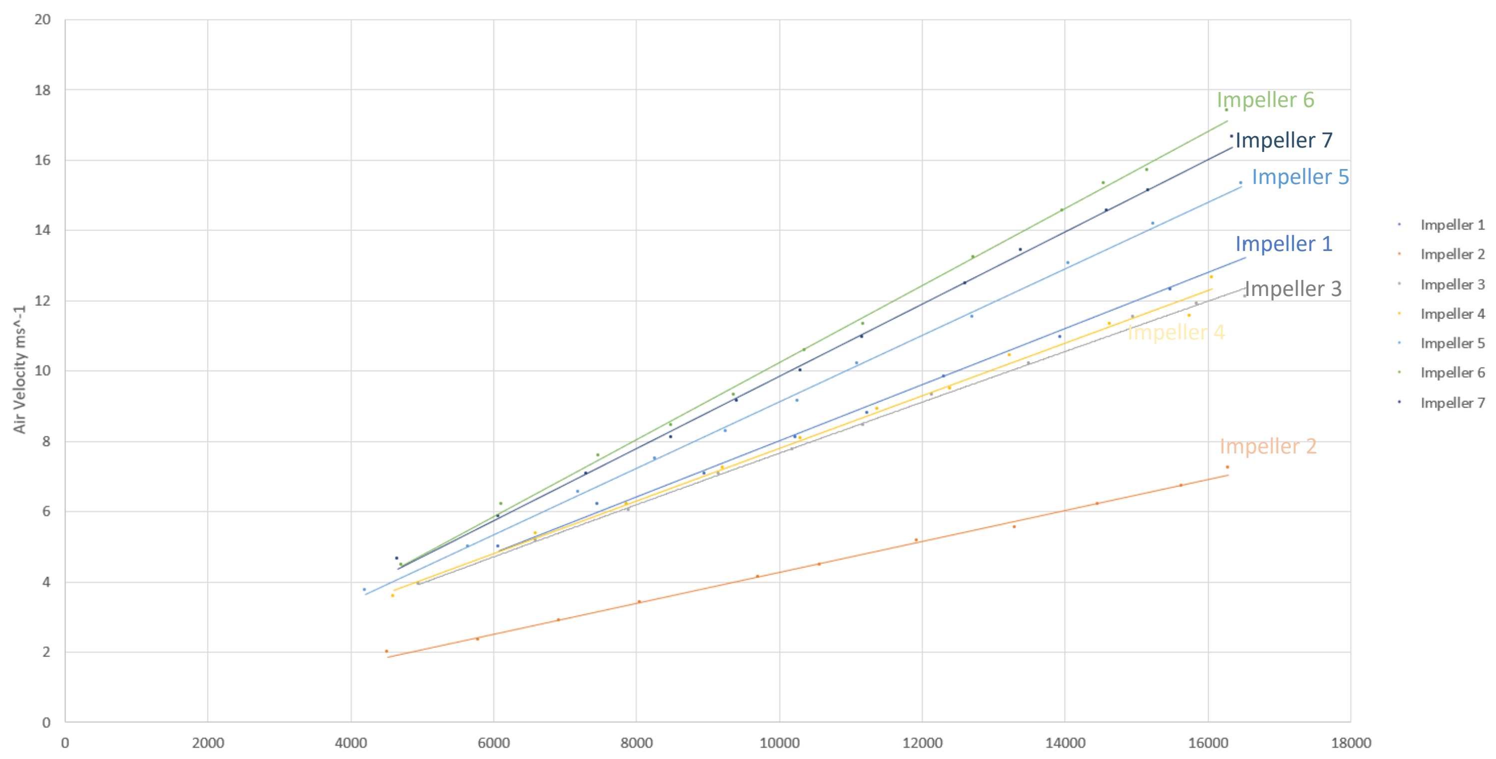
I also found that the black tape was too problematic and unnecessary since the plastic was matte enough to not reflect the laser back. Instead I used piece of clear tape to stick the reflect strip down and using glue secure the edges of the tape. This was done as the tape under the high speeds started to be unstick slightly, air would get underneath the tape blowing it out, causing it get caught by the casing where it would be eroded as well as creating a large amount of annoying noise; this was found through my testing. The glue would prevent the air from catching underneath the tape as well as further securing it since the tape did not stick well to the PLA.

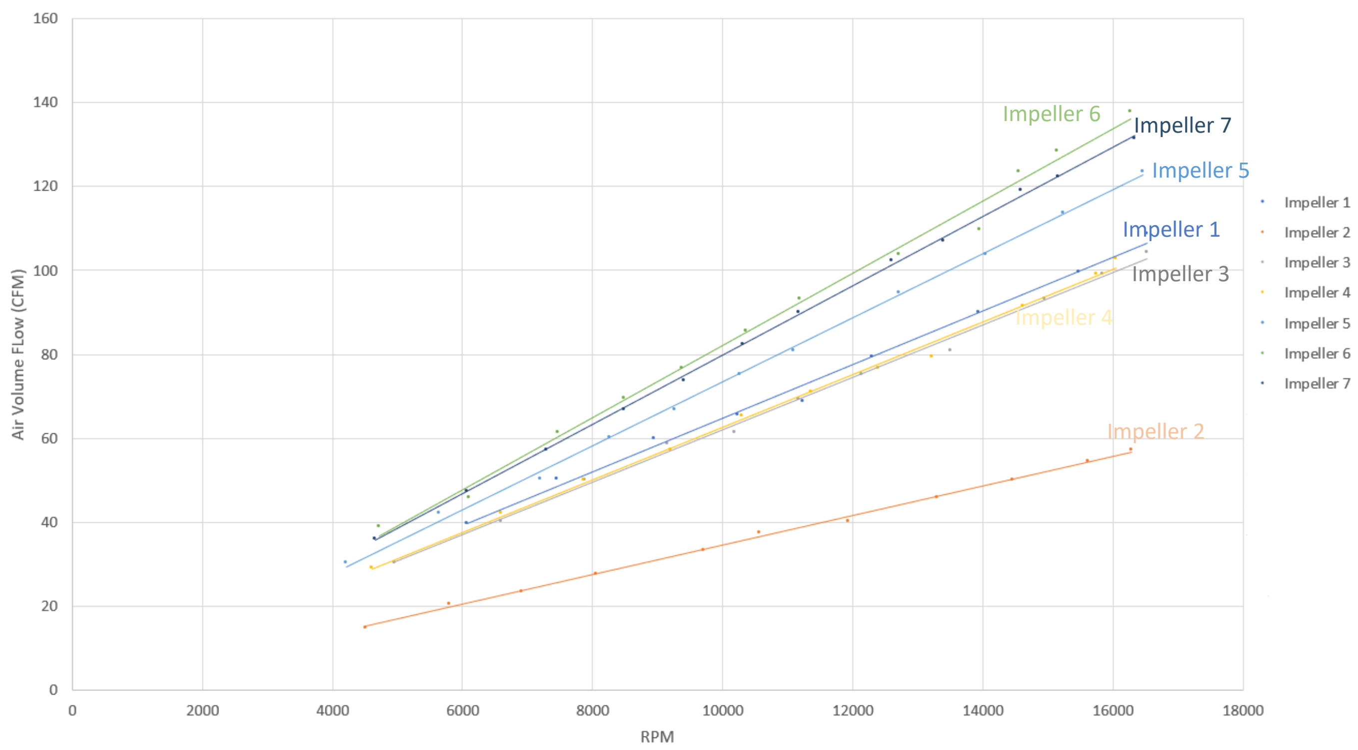
Testing



After ensuring the device was working correctly and checking that the measuring equipment had no issues, I could then get on with the testing of the impellers' performance, looking at the impeller's airflow and air velocity at the outlet across a RPM range. The anemometer was used to measure airflow and air velocity. The RPM range was from around 4500rpm to 16500rpm where ~4500 was the lowest sustainable RPM possible meanwhile 16500 was not anywhere close to the maximum speed that motor could go at but with how uncomfortably loud they were getting, it was unrealistic to use this speed anyway in a real life product.







Results

As a result of the data being collected, I could now display this onto a graph so that I can properly compare an analyse the results. I did not use a high enough max RPM to notice the performance starting to reduce which is a shame but such speeds are highly unrealistic for home use. I must note that the readings are not truly accurate and is less that the actual speed due to the anemometer not being able to be fully behind the

Impellers 1-4:

Impeller 1 is the original with impeller 2 with 5 blades, impeller 3 with 10, and impeller 4 with splitter blades (10 total). Impeller 2 was by far the worst with roughly around half the performance of the original. Although I knew that fewer blades were not good for a high pressure impeller, this really proves that low blade counts are far from ideal. However, due to less blades, it was lighter, putting less strain on the motor which would make it more reliable. Nevertheless, even compared to the other impellers, this one was incredibly loud, resulting with my ears ringing temporarily after the end of that particular test.

Impeller 3 had 10 blades whose output volume flow and air velocity a little lower than impeller 1. Impeller 4 had splitter blades, 5 regular blades, 5 splitter blades, totalling 10 in total. This achieved slightly better than the 10 blade version, being able to achieve this performance with 10 blades but reduced weight is beneficial, displaying that splitter blades does in fact increase suction. However, impeller 1 still outperformed it. This shows that 8 blades is the most optimal out of the different numbers.

Impellers 5-7:

These impellers are share the optimal 8 blades but have added benefits of thinner blades, slight aerofoil and a sharper angle of attack - this has had great improvement over the previous iterations. Impeller 5 only has a straight edge on its inlet blade but impellers 6 and 7 both have forward swept edges surpassing impeller 5.

Impeller 6 has the greatest performance reaching air velocities of around $17ms^{-1}$ which equates to about 61 km/h as well as air flow almost up to 150 CFM during the test - regular desk 120mm fan produces 30CFM at full throttle.

Conclusion:

Overall this project has been a success and through it I've had to tackle problems and issues, having to develop the design. With the propulsion unit prototype, I have achieved my goal of finding the best iteration of impeller design that would be used in my bladeless fan.