GO BRUSHLESS.COM
Your One-Stop Shop for Home-made Brushless Motors & Supplies

GB Kit v1.1
Single-stator brushless motor
(with ball bearings)

Tutorial & Troubleshooting Guide

Authors: Phil, Jay, & Steve   Version 2.0

Date	Initials	Description
2004-08-25	JC	Added stock motor cut away photo with enhancements made by Eric Tolladay

Introduction

Building homemade brushless motors, originally known as CD-ROM motors, used to be quite the task. To find the right parts was a pain-staking process involving the destruction of countless CD-ROM drives, and even when you found enough parts to build one motor, the odds of finding identical parts to build an identical motor were slim to none. GoBrushless.com remedied this problem by making homemade brushless motor components and accessories readily available – inexpensively – in any quantity needed. Now you can obtain the parts to build 10 identical motors or 10 completely unique motors.

Why is this important? Predicting the power output of a homemade brushless motor used to be a shot in the dark. The unavailability of standard parts meant that even when you successfully built a motor, reproducing the results was impossible. There was no way to determine exactly what the gain/loss would be from adding an extra turn or wind of wire, using a higher or lower wire gauge, stronger magnets, etc… With identical "standard" parts – a hobby-first from GoBrushless.com – this is all a thing of the past. No longer is the most difficult part of do-it-yourself brushless motors finding the right parts - now it's finding the time to build!

This tutorial is meant as a basic guideline to illustrate in the simplest manner how to make a homemade brushless motor using parts available from www.GoBrushless.com. There are many variables that determine the motor's performance characteristics. We'll get more into that on the website later. If you've never made one before, follow these instructions for your first try. You'll end up with a 20 turn, 12 pole motor that WILL work well. After you've shown yourself that it can be done, experiment with different number of turns of wire, different magnet configurations, etc. Who knows, before too long, you might be ready to try a double whopper with cheese (two stators wired as one). Hope you Enjoy☺

Conventions used in this text. We will use CW and CCW to mean clockwise and counter clockwise. A capital T following any number should be read as turns (26T = 26 turns). AWG is American wire gauge and will be used for all instructions. All dimensions are assumed to be metric unless otherwise specified.

****

Background

Background: The principle of electric motors is energy conversion. That is to say, we are converting electrical potential into mechanical movement. Furthermore, in our situation we will be dealing with permanent magnet (PM) brushless motors otherwise known as brushless DC or BLDC. The brushless part of the name refers to the fact that there are no physical brushes that commutate the current to the windings (as opposed to a brushed DC motor). You have to commutate the current to reverse the magnetic polarity in a winding. Without going into too much physics we refer to this as the right hand rule. Take your right hand and curl your fingers in the direction of the current. Your thumb points in the direction of the magnetic north pole. In a PM motor, there are two or more fixed permanent magnets set with alternating polarity and equal spacing around the rotor.

As the current is commutated, the magnetic fields switch direction (from N to S and from S to N). Like magnetic poles repel, and opposites attract. The stronger the magnet, the more the repelling force from the like pole and attractive force to the opposite pole. The strength of an electromagnet is directly rated to: 1) The number of Amp-turns and 2) The magnetic saturation of the iron core. The first is somewhat self-explanatory, but let's look at it a bit closer. The more amps you pump into a wire, the stronger the magnetic field. If you want to decrease your amps (keeping everything else constant), you can increase your number of turns. In our case we have two design limitations: the size/capacity of the battery and electronics, and the actual numbers of a physical wire size that will fit on the tooth of the stator. Of course, the two are inner-related too. The thinner the wire (higher the gauge) the less amps it can carry which means higher resistance and thus higher core losses. But the thinner the wire the more turns Now for number two. When you magnetize the core in one direction, then try to change its magnetic polarity by reversing the current, the power needed to do the reversal is greater than it took to magnetize it in the first place. This is known as hysterisis. As you up the amp-turns the iron atoms will reach a point that they are already aligned with the magnetic field and cannot carry any more flux. This is called magnetic saturation. Any power you put in above the saturation point will result in heating … plain-jane wasted energy for our purposes. The rule of thumb is 50W per single stator. More on that below.

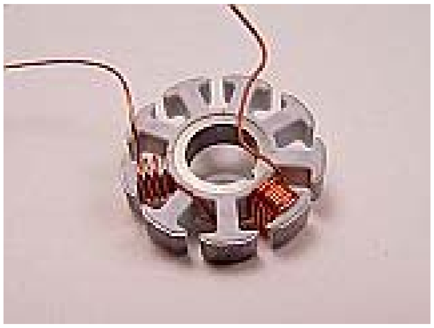
Materials needed

Gather all of the required components. Your kit includes 3 colors of 26 AWG wire, stator, can (or 'yoke', or bell), 5x5x1mm N45 magnets, 3mm shaft with integral washer, brass bearing holder, bearing sleeve, and two 3mm ID ball bearings. You will need wire cutters, a soldering iron and solder and heat shrink tubing, emery board or razor knife, slip-joint pliers or bench vice or even better a drill press, CyanoAcrylate (CA) glue, toothpicks, a bamboo skewer, a sharpie, and patience.

Step 1 – Winding the Stator

So where are we … well, we are going to create a single stator 3-phase synchronous AC permanent magnet motor using the stock parts of a commercial DVD drive for the purpose of flying smallish aircraft. The stator (or stationary part) of our motor is a 9-tooth 22.7mm diameter stack of thin silicon-steel laminations with integral end insulators to aid in our winding. Based on measurement data (or a wild hair) you will need to decide the number of winds for your motor. A very basic rule of thumb is, the fewer the winds, the hotter the motor the higher the Kv (RPM/V) the lower the Kt (torque) the higher the amps. Vice versa the more the winds, the lower the Kv, the lower the amps, and the higher the torque (better for 3D swinging a big prop slow). A high number of winds is 21T or higher and a low number is 14T and lower. Specific data points can be found in the gobrushless.com database where experimenters are encouraged to share their test results with everyone.

The key thing to remember is that these stators are wound using three phases. That means 9 teeth / number of phases = 3 teeth/phase. We will wind one phase at a time. Also, the convention used in this tutorial is this: The top of the stator is what will face the inside of the can, the bottom is where the wire ends will exit. Clockwise is the direction when the stator is viewed from the top, or the tooth is viewed straight on with the top of the stator facing up. In the end, it doesn't matter CW or CCW as long as you are consistent. As a vocabulary check, the image below is showing the bottom of the stator because we see the wire end on this side. I hope you are clear on this.



First use a razor or sharp knife to trim the little tit flush with the rest of the insulation. Using any of the 3 colors of wire, pick the tooth that has the channel on the ID inner diameter) behind it. See the photo to the left for clarification. It does not really matter what tooth you start with, but it will be easier to remember tooth 1 once they are all wound. Wind the tooth in a clockwise direction. The wire's insulation is tough, but don't abuse it any more than you have to. Start at the hub and work your way to the outer edge (hammerhead), then back down to the hub. With 26AWG wire you should have 9 turns for the bottom layer. If not then your winds are not tight enough. Use your finger nails, a bamboo skewer, or similar no metallic (or anything sharp enough to cut the insulation on the wire) to pack the windings (both on top of and in between the teeth) tight. This takes time and patience – neatness DOES count in getting a good wind. A wind is one complete circle around the tooth. The key word is complete. In the Image above, there are 4.75 turns. It is a good idea to keep a tally sheet to keep track of your turn (especially anything 20T and above. Having equal number of winds is crucial to proper operation. When you have wound tooth 1 of phase 1, you need to move two teeth CW and wind it the same number of turns. As you route your wire from tooth 1 phase 1 to tooth 2 phase 1 leave a bit of slack to clear the stator holder we will be inserting later. Alternatively (and shown in the photo) you can go over then under the skipped teeth. Only use this method for low count windings as it will rob a turn (thus only 8 will fit on these teeth with 26AWG wire) per tooth. Finish out this phase by skipping another two in a CW direction and winding tooth 3 phase 1. Be sure that the wire exits on the bottom. Remember half winds don't count so you can bring the tail back around the tooth (in a CW direction) to achieve this. Congratulations, you now have 1 phase completed. If you were a pessimist you would now check for shorting of the windings to the stator ;) We'll address this step in troubleshooting later.

Step 1b

This step just involves repeating what we just did for phase 1 for phase 2.You may choose to do a tri-colored stator or not. Your starting tooth is 1 tooth in the CW direction from tooth 1 of phase 1. I think now you understand why we explained our notation before we got started. Again, in the example picture we used the over-under method but then we only have 14T on this stator ;)

Step 1c

Repeat the same steps as above for the third phase. At the end of this you should have 6 wire ends. Set this aside and let's move on to the bearing holder portion of our motor.

Step 2 Assembling the bearing holder

The bearing holder is turned out of brass and is configured to work with the included shaft. We say this because you may chose to use your own shaft and need to understand this part. The stator will sit on the holder and due to manufacturing tolerances you may need a drop of CA to hold the stator stationary.

CAUTION: CA will eat, disintegrate, and otherwise remove the coating on the magnet wire supplied. Be extremely careful if/when using it around your newly wound stator…it would be a shame to have to start over.

Inside the top part of the bearing holder you will notice an inner rim. No matter if you are using the bushing or bearings they must sit at or below this rim. Otherwise, the integral plastic disc on the included shaft will not seat correctly. If you have ball bearings we recommend them, otherwise the bushing will suffice for rotational speeds of 15K and under. Refer to the above image to see the proper orientation of the bushing. As for bearings, try and place them as far apart (observing the inner rim as discussed above) as possible. Be extremely careful using CA to secure them … or use Loctite with the same care. Do not assemble your stator onto the holder at this point. We will need this bearing assembly to complete our rotor below.

Step 3 Assembling the rotor

The rotor is the part of our motor that moves or in this case rotates….DUH! Our motor is also called an outrunner since the rotor is on the outside of the stator (versus an inrunner). Our rotor consists of three parts: the can, the magnets, and the shaft. The can has to be made of or contain a ring of steel/iron to carry the magnet flux. It is sometimes called back iron. The magnets need to be as powerful as N45 or N48. Don't worry about what the 45 stands for just know that higher ratings are better but cost more for diminishing returns.

Step 3a Installing the magnets

Take your stack of 5x5x1 magnets and pick one side to be magnetic North. This is an arbitrary choice and there is no right or wrong answer. Starting at the top, use a Sharpie to mark the North side of every magnet in the stack. Now we are ready to line the magnets in the bell. Slide a magnet off the top of the stack and place it in the bell vertically on top of but butted up against one of the three nibs. That was a mouthful so refer to the picture. This will give you a guide as to the level that all other magnets should be installed at. Hint, if you leave your stack of magnets (North side up) stuck to the top of your bell it makes it easier to keep track of them.

Now you have your choice of methods to use. One of the easiest is to use the three nibs to align the first 3 North magnets. Center the magnet on the nib and then affix it with a **small amount** CA (thin CA is best, just wick **a little** behind the magnets). We will go back and add a bit more later once all magnets are set. Next, visually align the next 3 North magnets directly across from the three you just placed. Try to be as precise as you can but keep in mind that small deviations are not “that” bad. Congratulations, you are half way there. Again use a **small amount** of thin CA to wick in behind the magnets. To help actually position the magnets use an Xacto blade or a toothpick. Remember to keep the magnets at the same level as you place them. Now place the South magnets (the side with out the mark should face inward) between the North magnets. Don’t worry, expect the Souths to slide over to the Norths…remember opposites attract ;) Using two toothpicks (we like the kind that are round and taper to points) to evenly space the South magnets between the North magnets. Keeping the same level, work your way around. At the end, if you feel you need to wick another **small amount** and twist the bell to try and distribute the CA evenly. It is better to have too little and add than too much and have to remove the magnets, scrape/sand the excess and start over.

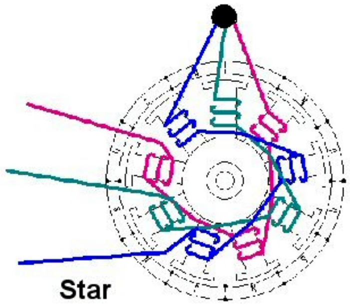
The other method is to print out a magnet placement template (see Appendix A) and use it to align your magnets. Just remember to place the magnets at the proper height. We have also added a calculator to the www.goBrushless.com website that will generate a magnet template for you given the stator, rotor, and magnet dimensions. Use 22.7, 25.5, 5, and 2 for the required dimensions. I place all of the North magnets first, making sure they are vertically aligned up the side of the bell, use thin CA to affix them, then add the South magnets and repeat. Afterwards you should remove the template. To prevent the template from being glued in, apply some petroleum jelly to the template first.

Step 3b- Installing the shaft

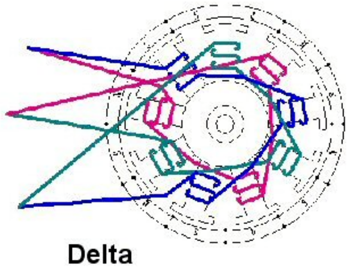
This is the single most frustrating step in the process. Take your time, align everything as best as you can, and go slow. We need to insert the shaft into the hole in the rotor. If we are off, the rotor will not spin true and worst case the rotor will rip itself apart as the magnets rub the stator teeth. The best option is to use a drill press to insert the shaft. Note that there are two sides to the shaft (with reference to the plastic disk). The shorter side gets inserted into the rotor. Your other option is the faithful shop vice. If you use the vice the trick is to increase the surface area supporting both the can and the shaft. To support the can use a socket the appropriate size. As for the shaft, use the completed bearing holder assembly. Again, align everything us to your best ability before you start to press the shaft into place. The picture does not show the use of the bearing assembly (sorry about this). However, experience now tells us this is the best alternative. You need to press it so the plastic disk rests against the shaft support of the can. Congratulations again, we now have a completed rotor assembly. If not, skip down to the troubleshooting section for help ☺ **Never, ever, ever, never should the rotor bell touch or contact any part of the stator. If it does, something is wrong and you will have a cascade of issues if you do not remedy the situation.**

Step 4 Stator assembly

Now you can assemble the stator to the bearing holder. Again only use CA if you think you need it and use it cautiously and **sparingly**. What's left you ask. Well now you have another design decision to make. You have 6 wires and two ways to terminate them. The more popular (and easiest) is the Wye (AKA star) connection. You take either the beginning 3 ends or ending three ends, twist them together and solder them. The other three connect to your ESC. It makes no sense to go into the why's and why not's in this document of Wye versus Delta. However, the majority of the brushless manufacturers have chosen Wye. There are 10+ threads about rebuilding CD-ROM motors for our uses that delve into this subject at some points verging on religion. You are welcome to "seek the truth" in those threads ;) As for the other termination, Delta is only slightly more complicated. You need to connect the 6 wires thusly: End of phase 3 to start of phase 1, end of phase 1 to start of phase 2, end of phase 2 to start of phase 3.



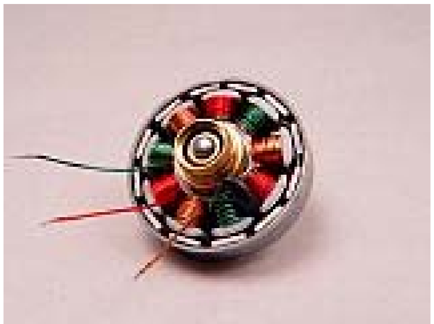
Star



Delta

Ok, if you insist here is the quick and dirty on Delta versus Wye. Wye uses fewer amps, gives more torque, and uses 1.7 times less number of turns versus a similar Delta wound motor. A delta can spin faster, uses more amps and is supposed to be more efficient. Happy now? If you want to go into more detail, I have included a post from Ezone in appendix B.

Ok, back to the tutorial. You need to remove the coating on the magnet wire to be able to tin and solder it. Emery boards work, but we find an Xacto knife will scrape the coating off easier. You want to keep your leads as short as possible, and use thicker stranded wire to get the length you may require. We use one inch when cutting the wires to length. Insulate the wires with heat shrink as appropriate (shown in the picture tucked in between two teeth is the Wye center connection).



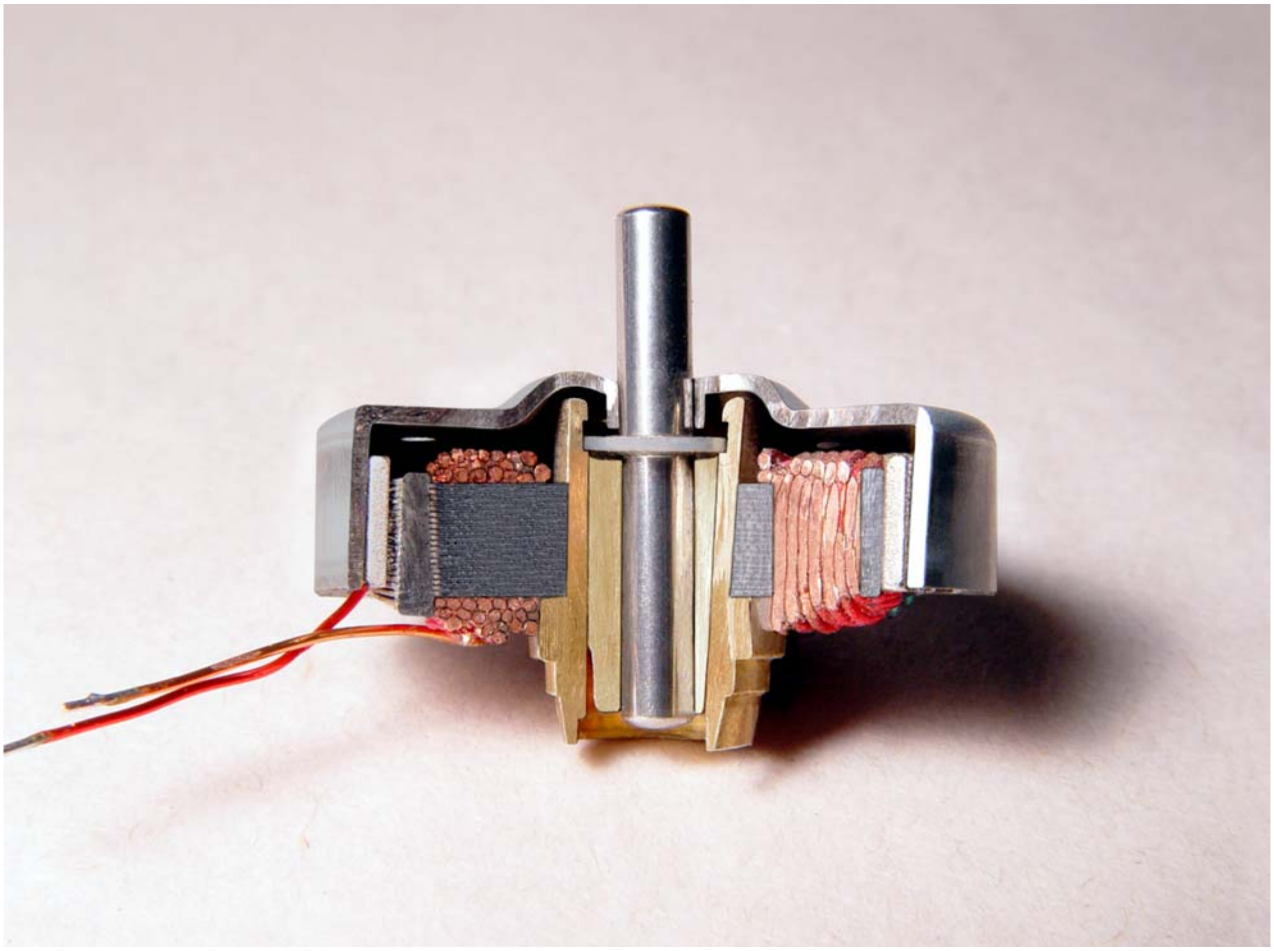


Figure 1 A cut away of a completed stock GBL motor. Special thanks to Eric Tolladay for enhancing this image.

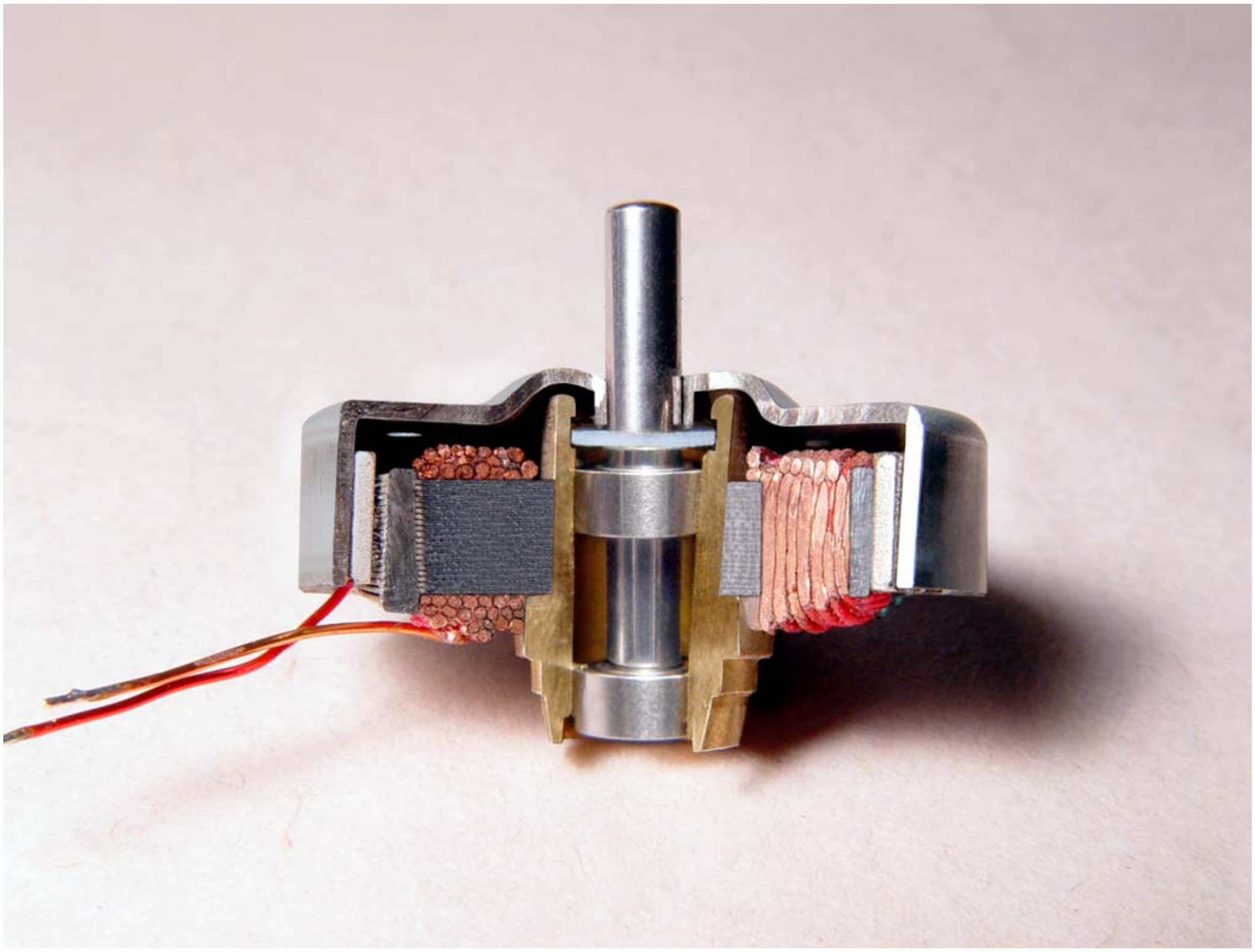
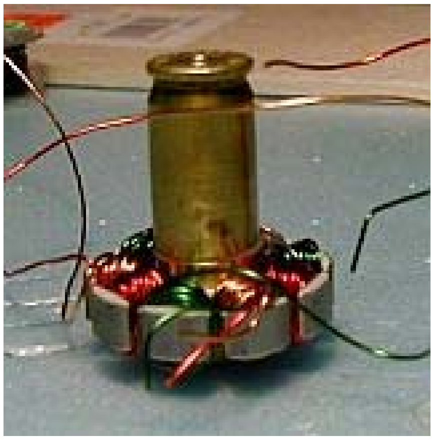
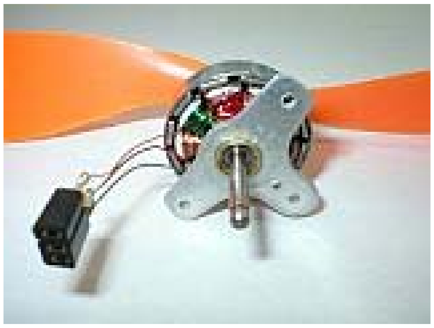


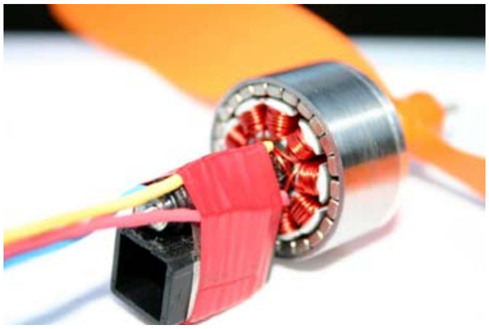
Figure 2 Cutaway showing the ball bearing option. Special thanks to Eric Tolladay for enhancing this image.

Mounting the motor

This section was not originally included, as there are a number of options that builders have devised that it would be silly to try and capture every one in this document. Again, your best resource for this is the eZone (www.rcgroups.com). However, there are some core methods that are used that bare mentioning. The most basic is to use a piece of tubing 11/32" or 9mm (brass, aluminum, carbon fiber, and plastic are all good materials) that joins to the back of the bearing holder (CA, JB weld, epoxy, solder, loctite, etc…). Then mount this to your plane with zip ties, balsa stick, carbon fiber, etc… Still others are taking GWS motor mounts and attaching the motors to them directly. Finally, a piece of metal with the brass bearing holder brazed to it or glued to a piece of ply will work too. It's your choice. Of course you can also buy custom parts that will make this a much easier task when they become available ;)





Troubleshooting

It happens, you were careful, counted all your winds, made sure your magnets were all lined up, did your best to press the shaft in straight, yet your motor runs poorly if at all. Find your symptom on the cart and follow the steps for remedy. If your problem is not listed (very rare) then submit it to us with the remedy and we'll add it. You can seek more immediate help on the Power Systems forum on eZone (www.rcgroups.com).

Issue	Cause	Remedy
My motor runs erratically if at all	Oh boy, this is such a broad problem that we'll have to approach it in steps. First and foremost we need to look for electrical shorts.	
	1. Shorts: A short is the short name for a short circuit. There are many different areas that could short but the most common is that the top of your stator (the windings that is) are physically rubbing the inside if the can. Thus several turns are being shorted (to the motor it looks like an imbalance of turns).	1. Pull the bell off, and use some method of gently flattening the top turns. Some builders now make it a habit of putting their completed stators between two board in a vice and giving them a squeeze before assembling the stator to the bearing holder. Others have used other methods involving crafting a spacer to fit between the plastic disk and the bearing or bushing to give a bit more clearance. In the future try to pull your windings tight as you wind.
	2. Bad termination: You did not connect the wires as directed, or your solder connection is poor.	2. For a wye termination you have to connect all the starts or all the ends. Any other combination will not work. As for delta, double-check the wires (use tri colored wiring for your first one). Now, inspect all of your wires. Be sure you removed all of the insulation before tinning. Make sure all connections are tight, and solder the ends together before you twist them. Use heat shrink to insulate the connections.
	3. Magnets: If your magnets are out of sequence then the back EMF waveform will	3. Double-check the magnet polarities around the bell using one

	confuse the ESC and your motor will not run. 4. Friction: Determine if you feel any physical resistance (rubbing, unusual friction, scraping sound). 5. ESC: Some esc's require advancement, some not, some soft start, some none.	of your spares. Verify attract-repel-attract-repel…it happens. Also verify as close to perfect alignment (i.e.: equal spacing) of your magnets. 4. Bell misalignment is the obvious culprit. You may have to reinsert the shaft. Double-check the concentricity of your rotor by chucking it up in a drill. If you see wobble there, then you have to re-insert it…if not, then the shaft is fine. With the rotor still chucked, spin it up and observer the inside of the can. Did you make sure not to install any magnets over the nibs? If they are, they will stick out too far and rub. Use an Xacto blade to pop them loose and re affix them per the instructions. If they look fine, then you can try to file the stator teeth down (never file neodymium magnets). Go back to #1 above and check for the winds rubbing the rotor. 5. Play with those settings 1 at a time. Next confirm that you are not going into LVC (use a fresh pack), and that you are not exceeding the max draw of the ESC.
2. My motor runs…YEA!!!, but starts to act erratic past half throttle ☹	1. Magnets: Are too weak. 2. Wiring: Intermittent connections or shorts.	1. If you heat your magnets above 80C they will start to demagnetize. If you are trying to use the stock ring magnet you are on your own ;) 2. Vibration or some other force is causing your wiring to rub intermittently, or else you have a weak solder joint (AKA cold solder joint). Some builders use tooth floss to wrap their windings to keep them from creeping. Others use red glpt a coating designed for the purpose.

Acknowledgements

We would like to thank the following people for their input and help in writing this tutorial:

Jay Couture (AKA Jay C): Provided all the photos in this revision rewriting the majority of the text from the first revision. He has coded the performance database and provided several motors and measurements to help people pick a wind that will work for them. Furthermore he has coded a motor simulation form and rotor calculator form with a dynamic magnet template creator.

Steve Metcalf (AKA ScubaSteve): Had an idea to buy the DVDROM parts and distribute them to all of us would-be experimenters at very affordable prices and extremely high quality. Steve provided some of the text in the intro on the GBL banner image. Steve continues to try to expand the sub hobby by getting new stator configurations, supplying high quality custom parts, and providing a single source for all things concerning these motors in the form of mini articles and tutorials like this one.

Phil Smith(AKA HappyHarry): Wrote the entire first version of the tutorial including all photos and text.

Eric Tolladay (AKA Tolladay): Has used his expertise to enhance the cut away photo to show the different components more clearly.

Ron van Sommeren: A catalyst for the entire spectrum of DIY brushless motors including CDROM rewinds and LRK motors. It you have a question (no matter how many times it’s been asked) Ron will always answer or know where to find one.

Don Armstrong (AKA bz1mcr): Don has provided feedback and suggestions from the start as well as a magnet template image included in this text.

Richard (AKA Rysium): Richard is an engineer, experimenter, and aspiring 3D pilot. He designed all of the custom parts, provided volumes of experiments for motor designs including magnet thickness, Delta over Wye, air gap width, and more.

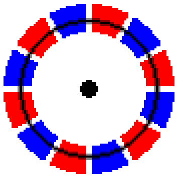
Martyn McKinney: Provided the original Excel spreadsheet and guidance for the motor Simulator form.

Appendix A Miscellaneous Information

Glossary

Io = no load current usually measured at WOT without an propeller
Kv = RPM per V or RPM/V
Rm = resistance of 1 phase of windings
bell = yoke = can = flux ring + end cap
delta = triangle
double = two stators stacked
flux ring = back iron … required to complete the magnetic flux circuit
pole = magnetic pole containing 1 or more magnets of similar magnet polarity
stator arm = stator tooth
triple = three stators stacked
whopper = a postfix used after double, triple, etc…
wind = turn = 1 complete loop around the stator arm
wye = star

Magnet templates



22.7mm 5mm mags

22.27mm 5mm mags

We now have a dynamic form that will create a magnet template based on the rotor, stator, and magnet measurements you provide.

Appendix B

(http://www.rcgroups.com/forums/showthread.php?t=249940)

Delta or wye

I personally chose Wye because less windings are needed for the same amount of torque (versus a delta wind) ... at least that's what we have been telling ourselves. Well, to try and put it to rest (yeah right) here are some links I've found via google.

1. This one links to a discussion board. To quote them

> Quote:
>
> The difference between the star and delta connections is the voltage required at a given frequency to produce the rotating field is the square root of 3 greater for the star connection compared to the delta connection.
>
> To keep the same field when the frequency changes the volts/hz ratio needs to be kept constant.
>
> For the low speed case, a voltage applied to the star connection would produce torque at lower speeds/frequencies. The voltage divided by 1.73 applied to the delta connection would provide the same torque.
>
> Raising the frequency to increase the speed would lower the volts/hz ratio and weaken the motor. When the motor is unable to produce the torque required at a given frequency, the motor can be changed to the delta connection which would be equivalent to raising the voltage by a factor of 1.73. This would produce torques at higher frequencies/speed until the point is reached where the field is weakened by the increase in frequency for a given voltage.
> ————————————————————————————————
> As stated by sreid, delta is not used in 3-phase bldc motors because of circulating currents. The voltage waveforms are rich in harmonics and in particular the 3rd harmonic causes a large circulating current at this frequency. This not only causes higher copper loss, but it also gives rise to a large torque ripple whilst contributing nothing to average torque.

2. This one from MicroMo says:

> Quote:
>
> Brushless DC-Servomotors
>
> In the 4490 ... B series, the windings are delta-connected. This results in higher motor currents together with lower voltages. These motors are particularly suitable for high-speed applications.
>
> Conversely, the prominent feature of the new 4490 ... BS is its high torque. The partwindings are star-connected. The motor currents are therefore lower, while the voltage is higher.

3. This one is the same thing but from Design News. Apparently (and I didn't catch this the first time) MicroMo and Faulhaber are the same company.

> Quote:

> The B series have delta-connected windings, reportedly resulting in higher motor currents with lower voltages. The BS series features star-connected windings and high torque; the motor currents are lower, and the voltage is higher, according to the company.

So, here's how I analyze it,
1. If you want more torque and use 3s then go for a wye wind. It will be slower but turn a bigger prop.
Advantages: Lower current = less wear on battery (lipos in particular) and esc
Can support higher voltages of 3 and 4s packs
Lower number of winds = easier to wind
No circulating currents
Are used by majority of commercial motor manufacturers both inside and outside the hobby

2. If you need more speed can source the current and use 2s, 7 or 6 cell packs go delta.
Advantages: More speed at lower voltages

Jay