Whiteboxᵀᴹ User Guide

Revision 1.2

October 7, 2016

Contents

1 Introduction

The Whitebox is our first public embodiment of Arx Pax's Magnetic Field Architecture (MFA^{TM}) technology. This is a prototype. The Whitebox is a play on 'black box, which is a device that has no explanation of its internal workings.

MFA was envisioned to efficiently shape magnetic field lines (magnetic flux) in order to produce "useful effects." In the case of the Whitebox, this useful effect is hovering a dynamic payload in a stable manner. To help you better understand the magic-ness of MFA, see **Section 6**.

Like many experimental technologies, the Whitebox should be approached with both great caution and respect. Again, we stress, its a prototype. A great deal of effort went into designing protection features and proper warnings/precautions on the Whitebox itself and in this User Guide. This is not like unpacking a blender and plugging it in. Each step matters, and we cannot encourage you enough to read through the User Guide carefully and thoroughly prior to getting started.

Beyond protection features, the Whitebox has gone through many design changes and iterations. Hover engine performance, runtime, payload capacity, and form factor were all altered to provide a wonderful and economical hover experience. A snapshot of the evolution of the Whitebox is shown below.

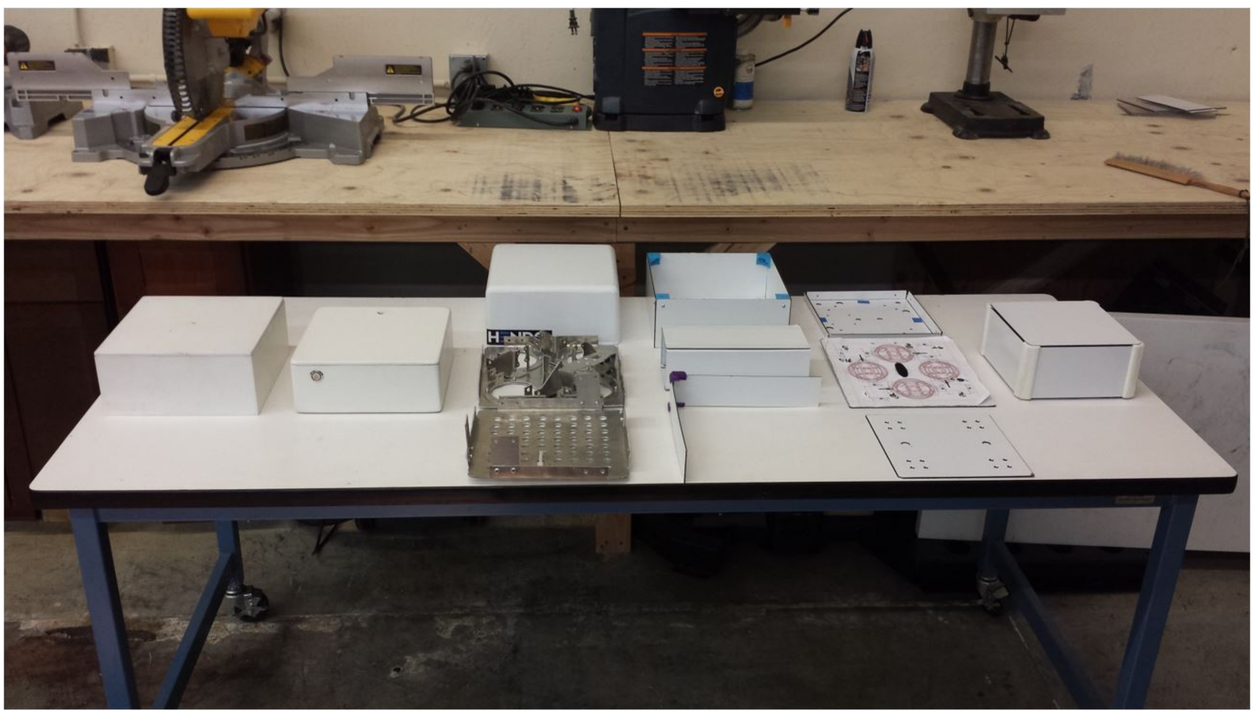


Figure 1: Sheet metal bending, 3D printing, vacuum forming and other manufacturing methods were experimented with for the Whitebox.

We sincerely hope you enjoy your Whitebox (safely!).

2 Equipment Not Included

Here is a list of the equipment we at Hendo use for Whitebox maintenance. These components help ensure safe, convenient, and long-lasting Whitebox operation. They are not, however, included with your Developer Kit. For some components, links are provided to specific parts that we have used and though we are not recommending these products, they have worked for us in our laboratory environment when used by our professional engineers. They may not work the same for you.

1. Battery Charger (only charged batteries should be used)
2. Battery Checker (only balanced batteries should be used)
3. LiPo Safety Bag (for safe charging)
4. 3mm Allen Key (for **Fuse Maintenance**)
5. Safety Glasses (safety first!)
6. A loop of tape (to help remove the top)
7. A non-slippary material (so items don't slip off the Whitebox top)
8. Barrier for hover surface (so that your Whitebox stays on the aluminum). See below:

2.1 Replacement Parts

1. DB Link AGU50 Fuse
2. LiPO Battery- Zippy Flightmax 5000mAh 3S1P 20C

   There is a wide range in the quality of hobby grade LiPO batteries. The Whitebox has been tested and optimized to work with the Zippy Flightmax 5000mAh 3S1P 20C. Though any LiPO battery can fail, including the battery just mentioned, operating the Whitebox with a different battery may lead to catastrophic engine failure and/or battery fire. Please keep this in mind when purchasing a replacement battery and never use a battery that is incompatible with the Whitebox and the required battery specifications provided in the user guide.

3 Whitebox Operation

3.1 Heat Cautions

3.1.1 Battery

According to the manufacturer, the LiPo battery used in the Whitebox should not exceed 60°C (140°F) degrees.

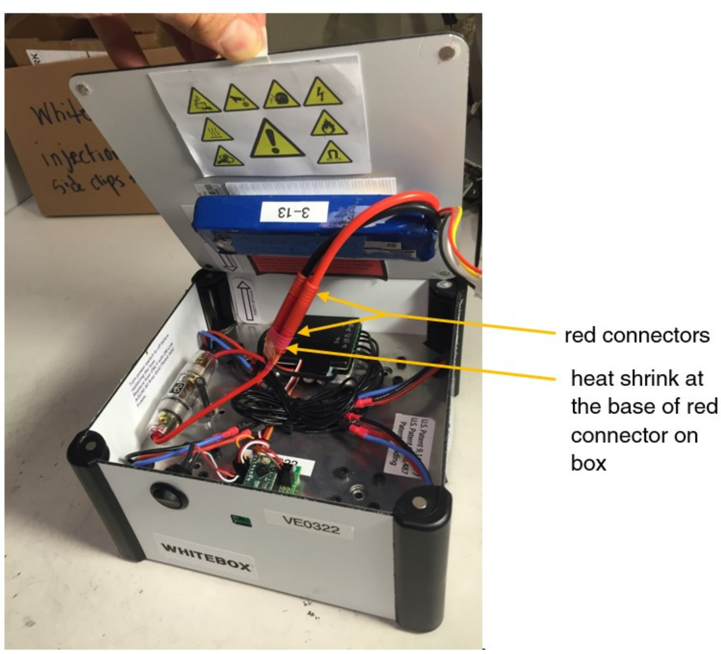
The Whitebox is equipped with a 5-minute timer and a 50A fuse to prevent over-heating and over-discharging the LiPo battery. Do not use any battery that does not match our specifications, do not disable the 5-minute timer, or bypass the fuse. Doing so could result in battery fire.

The battery can become warm (up to 50°C or 120°F) during the normal operation of the Whitebox.

3.1.2 Connectors

The red connectors that join the battery and the Whitebox will get hot during the normal operation of the Whitebox. The heatshrink at the base of the red connector in the Whitebox can get particularly hot (up to 70°C or 160°F) during use.

We recommend waiting 3 minutes before touching to allow these connectors and heat shrink to cool. Also, remember to always turn off power switch and unplug battery after use.



3.1.3 Surface

The aluminum hover surface will get hot during normal operation of the Whitebox. The longer the Whitebox runs and the more weight it carries results in higher surface temperatures. Temperatures up to 66°C or 150°F can be expected during normal operation.

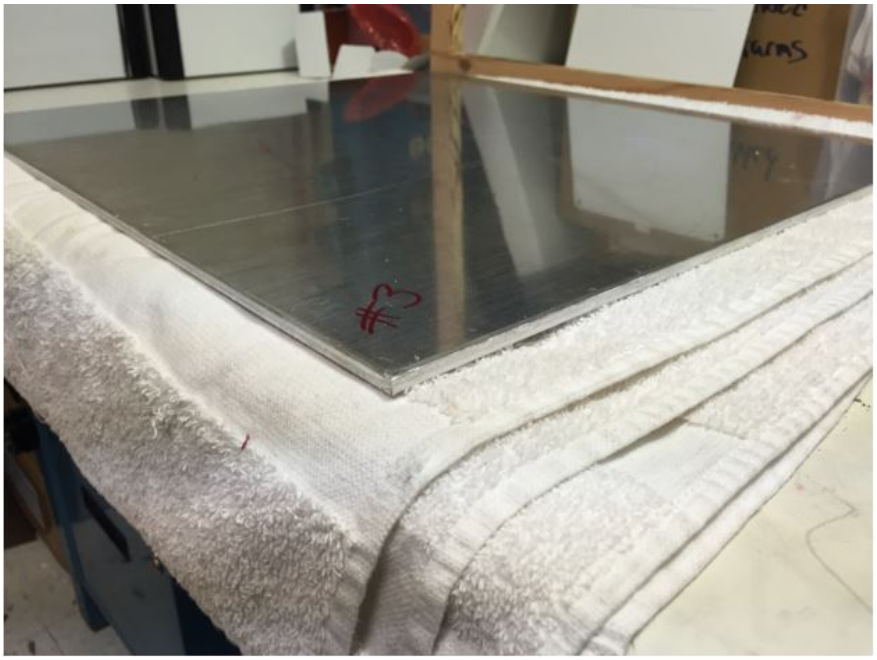
Allow the surface to cool completely before touching or moving. Do not operate Whitebox on any furniture or surface that cannot withstand temperatures up to 66°C or 150°F.

3.2 Preflight Instructions

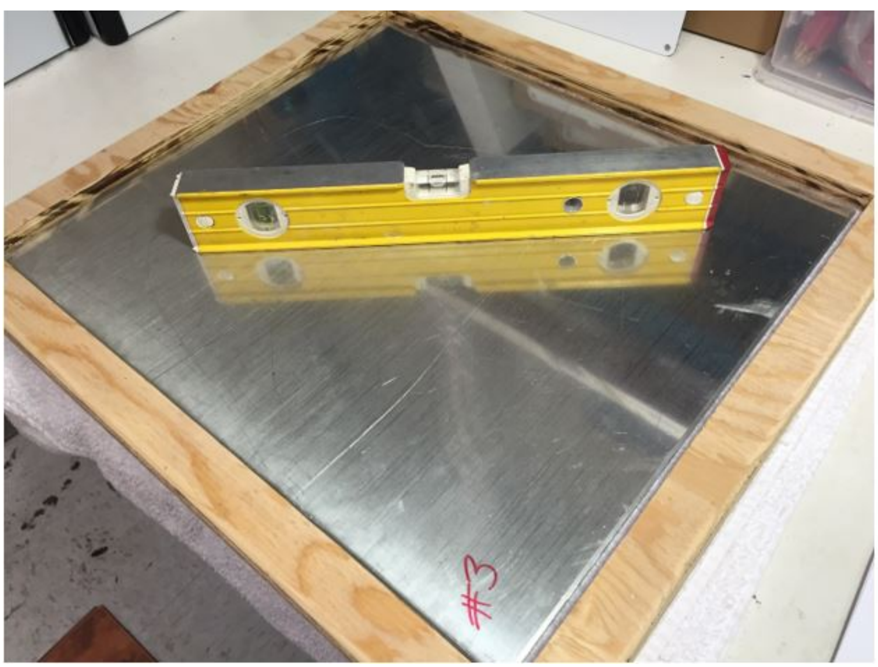
1. Charge the battery following the charger's instructions. Then, check the battery's cell balance. There are many definitions for when a battery is unbalanced. Our internal benchmark for unbalanced is any battery with cells that are more than 0.03V different from one another.

2. Do not use Whitebox on or near ferromagnetic surfaces (such as steel). The Whitebox will attract to the metal making it extremely difficult to remove.

3. Be cautious of where you put the aluminum substrate. The hover surface can get up to 66°C or 150°F and damage the surface underneath. Placing a towel or other barrier underneath the hover surface may aid in protection of the table or desk.



4. Ensure the surface is leveled.



5. Make sure that aluminum hover surface is free of debris (i.e. tools). A barricade can help with making sure the Whitebox remains above the hover surface.

6. Check the Whitebox hover engines for any stray objects that can become projectiles.

7. Inspect fuse caps for signs of melting. If the caps are damaged, consult **Section 4.3** for further instruction.

8. Make sure the power switch is in the off position (for a picture of ON vs OFF, **click here**). Then, connect the battery to the ESC.

9. Attach the battery to the Whitebox top.

10. Place the Whitebox in the center of the aluminum surface.

11. Flip the switch to the up position.

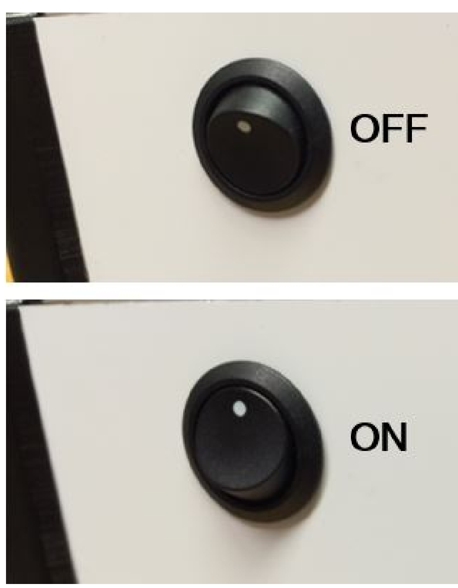
12. Keep the Whitebox on the aluminum hover surface. For optimal runtime performance, move the Whitebox around the surface. The Whitebox times out at 5 minutes to let you know that it is time to recharge your battery. If it has been less than 5 minutes, check the fuse.

13. Have Fun!

3.3 Postflight Checklist

1. Do not touch or move hover surface until it has cooled.

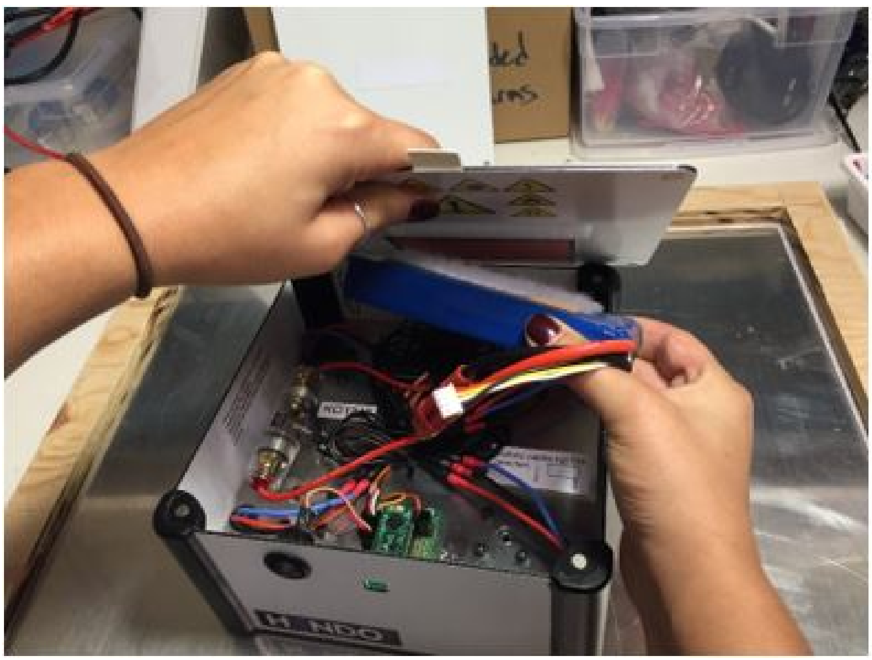
2. Ensure power switch is in OFF position.
   (a) If the timer cuts power or the fuse blows, the power switch will remain in the ON position.



3. Wait three minutes to open lid.
    (a) The battery and connectors need to cool before touching.

WAIT...

4. Lift lid at front edge, slowly peel battery from Velcro.
    (a) The wires are not long enough to remove lid from the box without detaching battery, take care not to stress connections at ESC and fuse.



5. Unplug battery.
   (a) leaving battery plugged in will over discharge it and permanently ruin it.

6. Store battery in a fire safe area or LiPo bag.

3.4 Runtime vs Payload

The Whitebox is programmed with a 5 minute run timer to prevent over-heating and over-discharging the provided LiPo battery. After every run, the battery should be allowed to cool and then needs to be recharged.

The max payload for the Whitebox is 2.5 pounds (1.1kg). For any payload over 1 pound (.5kg), the fuse should blow before the 5-minute timer cuts power to the box. We recommend that you order spare fuses if you are going to put any weight on the Whitebox.

The Whitebox is equipped with a 50A Fuse to help protect the battery. Under normal conditions with payloads of 1.0 pounds or less, the fuse should not blow. If the fuse does blow, refer to **Fuse Replacement**.

If the fuse blew, but no payload was placed on the box, check out section **Fuse Maintenance**.

The larger the weight put on the Whitebox, the more power and current that is required. As the voltage of the battery drains over time, the current draw increases and gets closer to the 50A cutoff of the fuse. The time it takes to hit 50A for given payloads is shown below.

Paylaod (lbs)	Runtime (minutes)
0	5
0.5	5
1	5
1.5	4.67
2	2.83
2.5	2.5

Table 1: How loading the Whitebox affects runtime, generally. Note, below 1 pound, the timer should cause the Whitebox to shut off before the fuse blows.

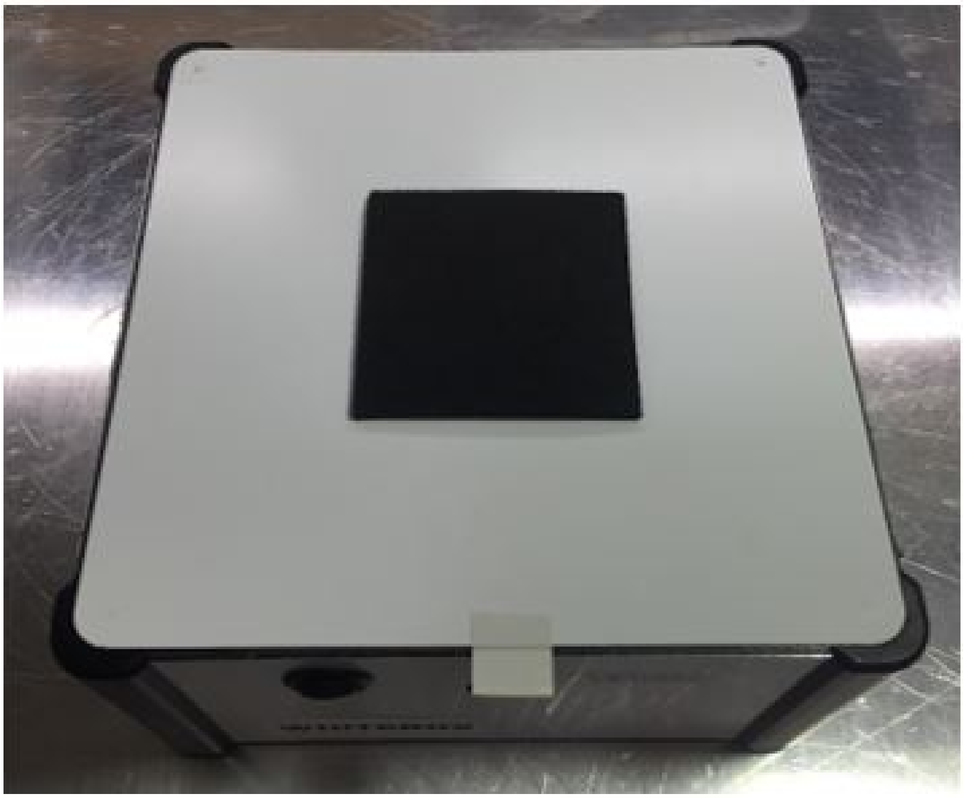
The information in Table 1 was gathered from numerous trials; however, the Whiteboxes we ship out are not tested through a full sweep of runtimes and payloads. We have noticed significant variation based on the variables listed below:

1. **Variation in the Whitebox's components**. Hover engines, batteries, ESCs, fuse holders, and other components all affect the current draw of the system, which means a defect in any one of them can cause the fuse to blow at a time different than listed above.
2. **Variation in the fuse**. We have seen a wide range of filament sizes and casing qualities, which leads to a deviation in runtime.
3. **Fuse cycles**. The fuse can degrade over multiple runs, especially if it was operated close to its capacity (50A).
4. **Hover surface temperature**. To maximize runtime, we recommend that you do not allow the Whitebox to hover in a stationary position for a long time. When the Whitebox hovers in a stationary position, the temperature of the surface increases, increasing the resistance of the material and the power requirement of the Whitebox to hover.

3.5 Putting Things on the Whitebox

The spinning of the Starm and motor causes vibrations in the Whitebox. Some vibrations can be so strong that they cause any items on top of the Whitebox to fall off. Therefore, we recommend that you take the following steps:

1. Place non-slippery material (such as a mousepad) in the center of the lid



2. Place object on top of the non-slippery material making sure the weight is evenly distributed among all four hover engines (Do not exceed 2.5 lbs)

3. Avoid placing any objects near the sides or edges of the Whitebox

3.6 Summary

3.6.1 Preflight

1. Charge the battery.
2. Check the battery's cell balance
3. Do not use Whitebox on or near ferromagnetic surfaces (such as steel).
4. Be cautious of where you put the aluminum substrate, it can get hot.
5. Ensure the surface is leveled
6. Make sure that aluminum hover surface is free of debris (i.e. tools).
7. Check the Whiteboxs hover engines for any stray objects that can become projectiles.
8. Inspect fuse caps for signs of melting.
9. Make sure the power switch is in the off position. Then, connect the battery to the ESC
10. Attach the battery to the Whitebox top
11. Place the Whitebox in the center of the aluminum surface
12. Flip the switch to the up position
13. Keep the Whitebox on the aluminum hover surface

3.6.2 Postflight

1. Do not touch or move hover surface until it has cooled
2. Ensure power switch is in OFF position
3. Wait three minutes to open lid
4. Lift lid at front edge, slowly peel battery from Velcro
5. Unplug battery
6. Store battery in a fire safe area or LiPo bag

3.6.3 Putting Things on the Whitebox

1. Make sure any item is kept centered on the Whitebox top.
2. Putting weight on the Whitebox increases the risk of blowing the fuse.
3. A non-slip material is useful if items are falling off.

4 Maintenance

4.1 Battery Charging Tips

As we stated earlier, we are not recommending any particular products, as certain products may have worked for us in our laboratory environment when used by our professional engineers and scientists but they may not work the same for you. For your convenience, we can tell you that the iMax B6AC V2 Charger is one that has worked well for us when charging the Whitebox battery. Regardless of what battery charger is used, below are some helpful tips:

1. Make sure you have the right adapter to charge the Whitebox battery. The battery has a 4mm HXT connector on it. An example of an adapter that works for some charger is here.
2. Charge in a LiPo safety bag
3. Check the cell balance post charging. There are many definitions for when a battery is unbalanced. Our internal benchmark for unbalanced is any battery with cells that are more than 0.03V different from one another.
4. Do not charge above 1C. The C rating depends on the capacity of the battery. For a 5000mAh battery (what comes with the Whitebox), 1C is 5A.

4.2 Fuse Replacement

This section requries a 3mm allen key

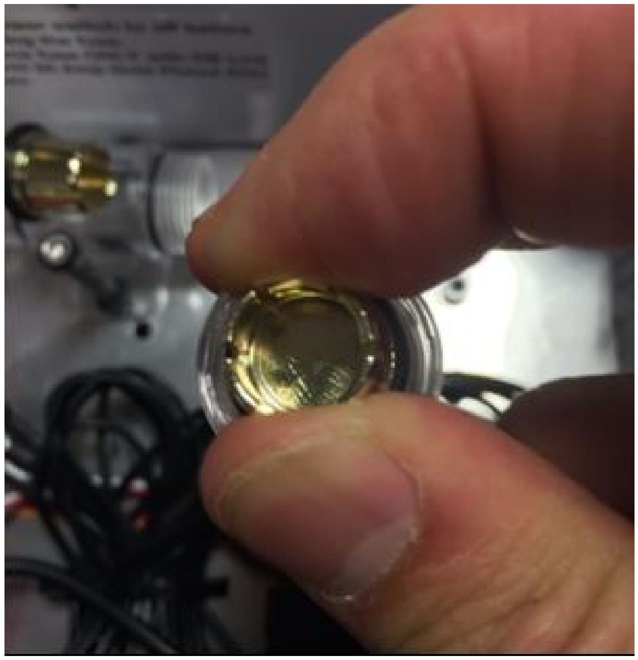
1. Ensure power switch is off, detach and disconnect battery

2. Wait for the fuse to cool, then unscrew the end terminals

3. Once the end terminals have been unfastened, remove the brolen fuse

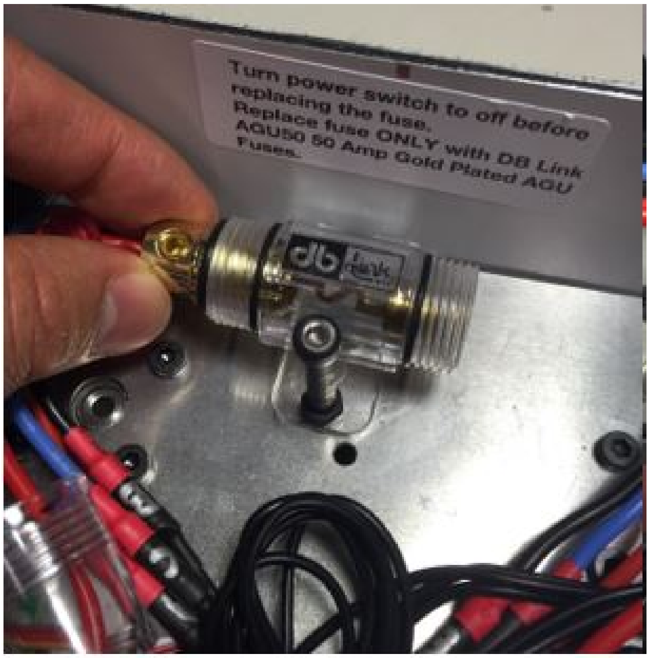
4. Check the end terminals for a secure wire connection, if loosened, proceed to securely tighten the set screws with the 3mm hex key

5. Ensure the fuse fit in the end terminal is tight by finger tightening the clamps



6. Place the new 50 AMP fuse in the end terminal

7. Place the fuse-holding end terminal in the db link housing (ensure the set screw is facing up for proper assembly)



8. Align the end terminal with the new fuse and insert it into the fuse holder

9. Ensure the set screw is facing up for proper assembly, the o-ring in the end terminal should touch the fuse holder.

10. Secure the end terminals with their corresponding plastic housing ends

4.3 Fuse Maintenance

1. Prior to each use of the Whitebox, inspect the red end caps of the fuse holder.

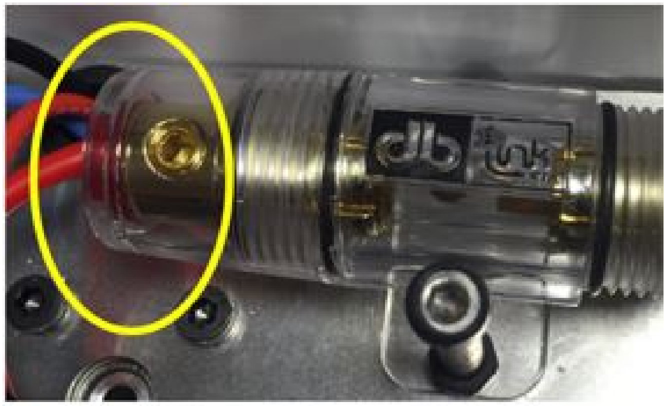


Figure 2: Fuse End Cap

Looking through the clear holder (**Figure 2**), you want to see intact red end caps that are not melted or discolored from heat. The photos below (**Figure 3**) show examples of good and bad end caps. The parts have been removed from the holder for clear photos. It should be possible to see discoloration or melting through the transparent fuse holder.

Figure 3: Good vs Bad End Caps

2. If red end caps are are intact and not discolored or melted from heat, the Whitebox fuse should be in working order.

3. If red end caps are are discolored or melted from heat, you will need to perform the maintenance described in steps 4-6.

4. Unscrew the clear cap covering the fuse ends (no tools are required for this) to expose the end caps and set screws that holds the red wires in place.

5. Gently wiggle each red wire near gold fixtures. If either is loose, there will be poor electrical contact which creates resistance and heat which will melt the end caps and can cause the fuse to blow below the rated limit (50A). If there is any wiggle between the inner and outer cylinders (**Figure 4**) or if the wire is not firmly clamped to inner cylinder, you will need to tighten the set screw with a size 3 metric allen wrench (**Figure 5**). Make sure that the wire is inserted far enough that the set screw engages the full area of exposed wire, but does not clamp the insulation on the wire.

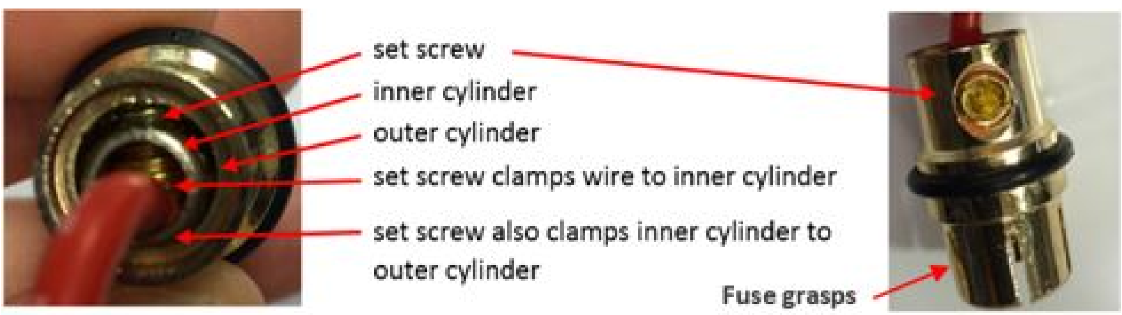


Figure 4: Labeled Fuse Holder

Figure 5: Adjusting the Fuse Set Screw

6. Also test to see if the fuse grasps (**Figure 4**) are holding fuse secure. The fuse should be easy to put into the grasps but held secure. If the grasps are loose, remove the fuse and squeeze the grasp with your fingers. Try the fuse again. Adjust until fuse is held securely.

5 Troubleshooting

5.1 Wiring

This subsection shows the proper wiring of the different components in the Whitebox. Checking the wiring is a great place to start when things go wrong, especially when only one part is not functioning as intended (i.e. one Hover Engine is not spinning).

5.1.1 Teensy Microcontroller Wiring

1. The Electronic Speed Controller (ESC) has 4 servo connectors coming out of it. These are what read in the throttle signal that causes the motors to spin.

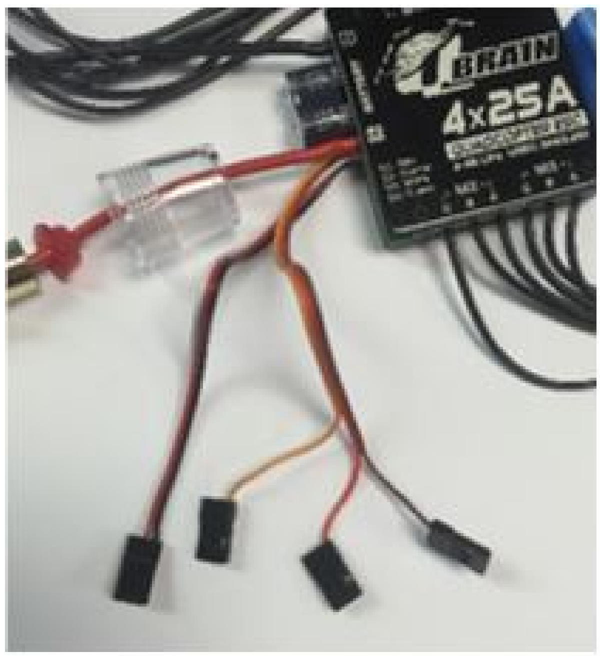


Figure 6: Signal 1 (S1): Red, Signal 2 (S2): Orange, Signal 3 (S3): White, Signal 4 (S4): Brown

2. Insert the 4 servo connectors from the ESC into the mating male header pins (pins 9, 10, 16, and 17). Orient the connectors so the signal wires (red, orange, white, and brown) are always closest to the Teensy Microcontroller. The correct ordering of the wires is shown below.

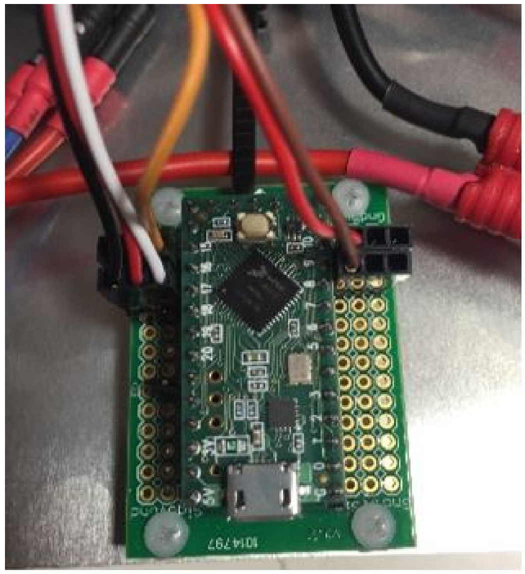


Figure 7: Placement of S1 - S4

3. The last remaining male header pin (pin 21) is where the power switch connects. Again, make sure the signal wire (white) is closest to the Teensy Microcontroller. The correct orientation is shown below.

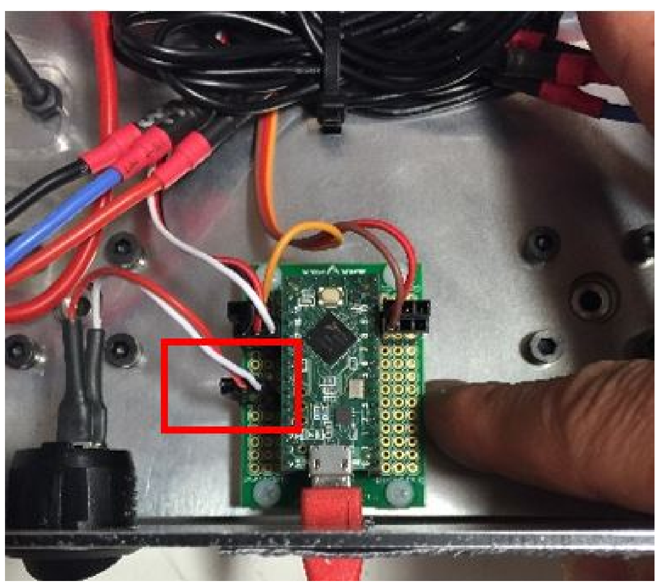


Figure 8: Placement of the Power Switch Wires

5.1.2 ESC Wiring

The order that the three motor leads for each motor are connected to the ESC affects the direction that the Hover Engine will spin. Each Hover Engine should spin counter to both adjacent neighbors such that the net torque on the Whitebox is minimized. Following the below wiring diagram will ensure that the Hover Engines are spinning in the proper direction.

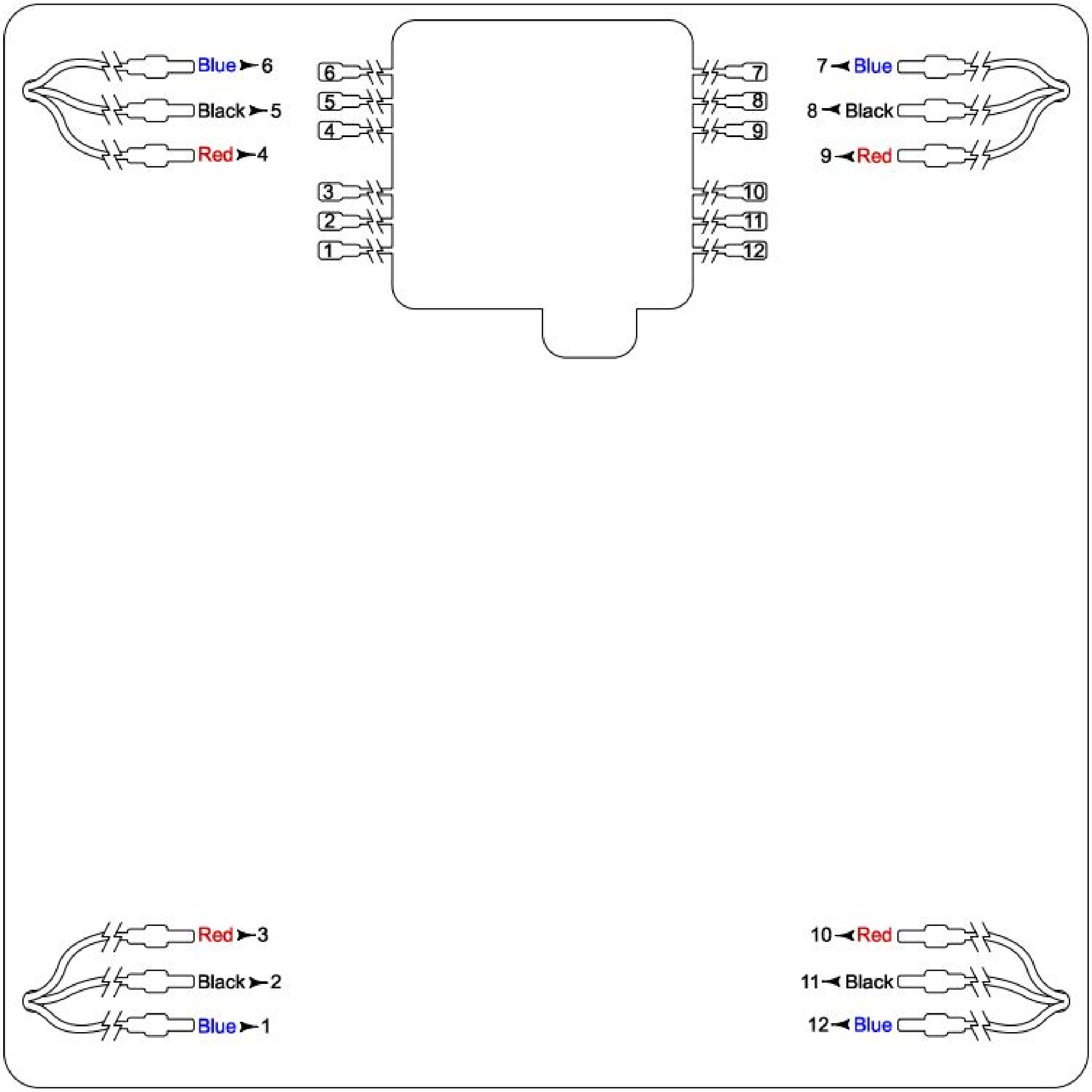


Figure 9: How to Connect the Hover Engine Leads to the ESC. This is a top down view of the inside of the Whitebox with the four sets of hover engine wires shown in the corners.

5.2 Scenarios

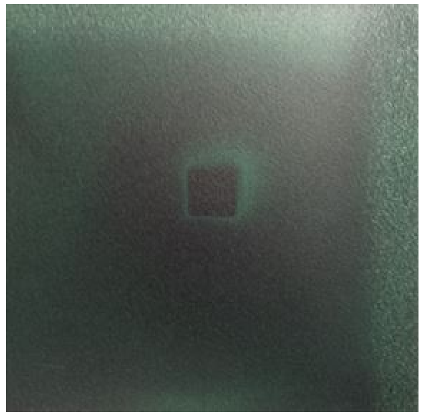
1. The Whitebox stopped suddenly while hovering and the power switch was not turned off.
   (a) The Whitebox is set up to stop after 5 minutes to prevent over-heating and over-discharging the LiPo battery. At this point, the battery will also need to be recharged. Allow the battery to cool to room temperature before charging.
   (b) The Whitebox is equipped with a 50A safety fuse (DB Link AGU50 50 Amp Gold AGU Fuse). When loaded with less than 1 pound of payload the Whitebox should not blow the fuse; however there are many factors that can alter performance (see **Section 3.4**). Refer to **Section 4.2** for fuse replacement.
      i. If the fuse blew but no payload was placed on the box, refer to **Section 4.3**.
   (c) Check that all wires are connected to Teensy Microcontroller, see diagram and photos in **Section 5.1.1**.
2. My Whitebox won't turn on.
   (a) The Whitebox is set up to stop after 5 minutes to prevent over-heating and over-discharging the LiPO battery. At this point, the battery will also need to be recharged. Allow the battery to cool to room temperature before charging. Plugging in a properly recharged and balanced battery will allow the box to turn on.
   (b) The Whitebox is equipped with a 50A safety fuse (DB Link AGU50 50 Amp Gold AGU Fuse). Under normal conditions with payloads of 1.2 pounds or less, the Whitebox should not blow the fuse. If this limit was exceeded (see **Section 3.4**), the fuse may have blown. Refer to **Section 4.2** for fuse replacement.
      i. If the fuse blew but no payload was placed on the box, refer to **Section 4.3**.
   (c) Check that all wires are connected to Teensy Microcontroller, see diagram and photos in **Section 5.1.1**.
3. The box is spinning like crazy. Note: A spin of 90 degrees in 3 sec or more in either direction is normal for this prototype.
   (a) It is rare, but a connector may have come loose. Check that all wires are connected to Teensy Microcontroller, see diagram and photos in **Section 5.1.1**.
   (b) Did you disassemble your Whitebox? If so, you may have some motors connected to the ESC in a way that has them spinning in the wrong direction relative to each other, see diagram and photos in **Section 5.1.2**. Motor spin direction is important, each Hover Engine should spin counter to those closest to it. Be sure to wear eye protection when operating the box on its side to check spin direction of each motor.

4. Somethings smells like it could be burning.
   (a) Turn the Whitebox off.
   (b) Check fuse and red end caps for signs of melting. Refer to **Section 4.2** and **Section 4.3**.
   (c) Check the heatshrink on the red connector (in box) for signs of melting.
   (d) Inspect the battery for puffiness or exposed wires.
5. The Whitebox is really loud or vibrates too much.
   (a) Turn the Whitebox off.
   (b) The Whitebox does have a distinct sound and a certain amount of vibration. To make this prototype affordable, it was designed with hobby-grade components and mounted to a light weight chassis. This experimental prototype was not optimized for noise or vibration reduction. However, try the steps listed below.
   (c) Check that all of the engine mount screws are tight (these 4 sets of 4 screws are visible when the lid is open; they are mounted toward the corners)
   (d) Check that all of the side panels are pressed into side clips (black corner pieces).
   (e) Ensure that all other (fuse, Teensy board, and ESC) mounting screws are tight.

6 Appendix 1: Understanding MFA

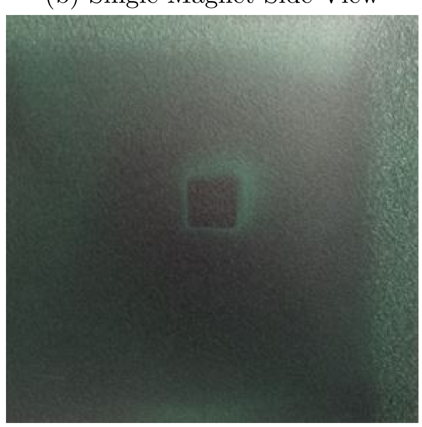
The small 4 inch x 4 inch green square that was included with the Whitebox is magnetic viewing film. Magnetic viewing film is a powerful tool for visualizing magnetic field lines. The film contains tiny particles of nickel, which arrange themselves in certain geometries when exposed to a magnetic field. When the magnetic field lines are parallel to the magnetic viewing film, the film will turn whitish and when the field lines are perpendicular to the film, the film will become a dark green. Examples of this effect are shown with various magnetic arrays below:

6.1 Single Magnet



(a) Single Magnet Top View

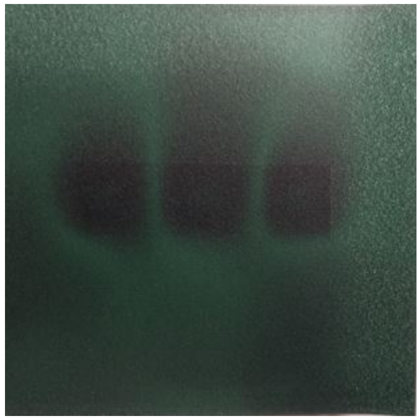
(b) Single Magnet Side View



(c) Single Magnet Bottom View

Figure 10: In terms of magnetic field density, the north pole and south pole of a magnet are identical. A hover engine built with just a normal magnet array leaves half of the magnetic flux wasted because half would be pointed away from the substrate and would not be used for hovering.

6.2 Linear Halbach Array



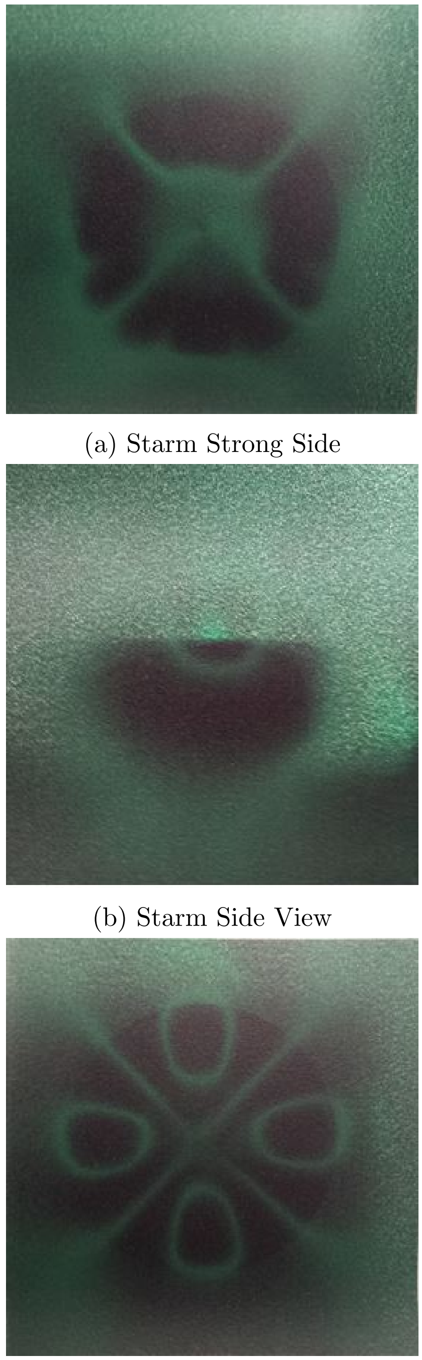
(a) Linear Halbach Strong Side

(b) Linear Halbach Side View

(c) Linear Halbach Weak Side

Figure 11: A Halbach array is a clever way to arrange magnets such that most of the magnetic field lines are diverted to one side, creating a 'strong side' and a 'weak side'. Linear Halbach arrays provide excellent lift when translating in one direction.

6.3 Whitebox Starm (Arx Pax magnetic array)



(a) Starm Strong Side

(b) Starm Side View

(c) Starm Weak Side

Figure 12: The Starm came about by understanding the benefits of a Halbach array and then improving it by creating radial magnetic field lines. When a Starm is attached to a motor, stable hovering can occur in a stationary position to enable hoverboards, Whiteboxes and other systems.

7 Revision History

1. Rev 1.0 April 16, 2016

   Original release of Whitebox User Guide

2. Rev 1.1 September 1, 2016

   Updated revision number to 1.1

   Updated revision date from April 22, 2016 to September 1, 2016

   Added text to **Battery** to clarify warnings and specifications for replacement batteries.

3. Rev 1.2 October 7, 2016

   Updated revision number to 1.2

   Updated revision date from September 1, 2016 to October 7

   Removed hyperlink to LiPO battery and replaced with name and specification (see **Section 2.1**)

   Changed internal benchmark for unbalanced batteries from 0.10V to 0.03V in **Section 3.2** no. 1.

   Changed internal benchmark for unbalanced batteries from 0.10V to 0.03V in **Section 4.1** no. 3.