# Brushless Motor Project

## 1 Introduction

Advances in semiconductor technology have made brushless motors the leading motor technology in a wide range of applications, including cooling fans in electronics, battery-operated power tools, robotics, and automobiles. Unlike brushed motors, brushless motors are controlled electronically, enabling unparalleled opportunities to optimize performance.

Electric motors convert electrical energy into mechanical energy. Generally the electrical energy generates a magnetic force between a **rotor** that rotates and a **stator** that is stationary. The resulting magnetic torque turns the motor.

The following figure illustrates the rotation of an electric motor in which permanent magnets attached to the rotor interact with electromagnets attached to the stator. In the left panel, the top and bottom coils are energized to produce magnetic fields that rotate the rotor so that its north pole is up and its south pole is down. In order to produce motion, the top and bottom coils are turned off and the next set of coils (clockwise) are turned on (second panel). This induces clockwise torque and spins the rotor (third panel) until it is aligned again with the magnetic field (last panel).

![Figure 1](image)

The important point of this illustration is that continuous motion of the rotor requires continuous changes in the magnetic field generated by the stator.

## 2 Commutation

A number of methods can be used to change the electrical excitation of a motor so as to control its rotation. The simplest method is to alter the pattern of excitation based solely on time – a process known as **synchronous operation**. For example, we can excite the top and bottom coils as shown in the left panel of **Figure 1** at time $t = 0$, then switch the excitation to the next set of coils (clockwise) at time $t = T$, then switch to the next coils at $t = 2T$, and continue this process. At $t = 6T$ the rotor will have completed one turn, so the motor will run at $\frac{1}{6T}$ turns per second.
In principle, we can adjust $T$ to get any arbitrary speed, but there are limitations, especially when turning the motor requires significant torque. Consider a motor that turns a fan. As the speed of the fan is increased, the torque generated by the air on the motor increases, and it therefore takes longer for the angle of the rotor to align with the applied magnetic field. If the stator field advances before the rotor has aligned with its previous position, then the rotor has even further to turn during the next time step. As the rotor “falls behind,” its speed will no longer match that of the applied electromagnetic field, and the resulting torque will become chaotic – giving rise to undesirable fluctuations and vibrations.

A more robust method for changing the electrical excitation of a motor is to control its rotation based (at least in part) on the current position of the rotor. For example, if the rotor is pointing upward (as in the left part of Figure 1), then we should excite the second set of coils (as in the second panel of that figure). As the rotor passes the halfway point in the third panel, the excitation should be switched to the third set of coils. Unlike synchronous operation where the decision for which coil to energize is based on time, here the decision is based on the angular position of the rotor. This method is known as commutation.

Commutation can be accomplished with a mechanical switch by attaching some parts of the switch to the rotor and other parts to the stator. An example is shown in Figure 2, where the switch consists of metallic plates (illustrated in red and blue) attached to the rotor, and brushes (illustrated as + and – to indicate the polarity of external power supply to which they are attached) that are attached to the stator. The left panel shows current passing through a coil in a downward direction that runs from the blue plate to the red plate. After rotating a quarter turn, the plates no longer contact the brushes and no current flows through the coil (center panel). After rotating half a turn, current again flows downward, but this now corresponds to current flowing from the red plate to the blue plate, which is opposite the original direction.

By switching the applied field based on the rotational position of the rotor, commutation provides a more graceful failure under load than was possible with synchronous operation. As the load on the motor increases, rotation slows (just as it did with synchronous operation). However, mechanical commutation automatically slows the rate at which the electric fields are switched, so that the rotational speed of the applied electromagnetic field matches that of the rotor, regardless of the load on the motor.

Figure 3 illustrates the commutator in a power drill. Three of the 12 commutator plates are visible in the center of the image. Carbon brushes are pressed against the plates by springs contained in metal sleeves positioned to the left and right of the plates. This type of mechanical commutator is widely used in motors found in household tools. However, a number of issues limit the use of such commutators in high power applications such as hybrid automobiles. Most importantly, electrical conduction through contact between even well designed brushes and the commutator plates is imperfect, generating sparks, producing
heat, and ultimately wasting power. Also, the relation between rotor angle and excitation is fixed by the mechanical design of the commutator. Other factors such as speed and torque cannot be used to optimize performance. For these reasons, fully electronic commutation in brushless designs are becoming increasingly important, as described in the following section.

3 Brushless Control of Electromagnets

Mechanical commutators perform two functions: they sense the rotational position of the rotor and switch the path of electrical current through electromagnets. Brushless motors use separate parts to accomplish the sensing and switching.

3.1 Sensing

One way to obtain information about the rotational position of the rotor is to use a Hall-effect device to sense the magnetic field produced by the rotor at a point that is attached to the stator (or vice versa). A Hall-effect device senses magnetic field strength by the interaction of magnetic fields with the flow of charged particles. Imagine that an external electrical source (such as a battery) generates a constant current $I$ as shown in Figure 4. If the current flows is to the right (in the positive $x$ direction), then electrons flow to the left. Application of a perpendicular magnetic field $B$ (in the positive $y$ direction) will generate a force called the Lorentz force on each electron in the positive $z$ direction, given by

$$f = qv \times B$$

where $v$ represents the velocity of an electron, $q$ represent its charge (which is negative for an electron), and $f$ represents the Lorentz force. The Lorentz force tends to push the electrons in the positive $y$ direction, and thereby generates an electrical potential that is more negative at the top of the conductor than it is at the bottom. By sensing the difference between the top and bottom surfaces of the conductor, we can determine the magnitude and direction of the applied magnetic field $B$.

Modern Hall-effect sensors are semiconductor devices of the type shown in the figure on the right. A constant flow of charged particles is generated by applying a constant, positive voltage (3 V to 6 V) to the left pin (red wire) relative to ground (black wire). The potential that results on the right pin (blue wire, relative to ground) is proportional to the strength of the magnetic field that passes through the black plastic face of the device, in the direction that is perpendicular to the plane of the image.
3.2 Switching

The current through an electromagnet can be switched with a transistor. A transistor is a three-terminal device in which the electrical conditions at an input pin (relative to ground) controls the electrical properties at a second (output) pin. In its simplest operation, the transistor behaves like a switch, allowing current to flow through the output pin (or not) depending on the state of the input pin.

The force between a magnet and an electromagnet can be attractive or repulsive depending on the orientation of the magnets and the direction of current flow through the electromagnet. **Figure 6** illustrates a simple scheme for electronically reversing the direction of the magnetic force by flipping the direction of current flow through the electromagnet using a circuit called an *H*-bridge.

![Figure 6](image)

An *H*-bridge consists of two half-bridges: one comprising X1H and X1L and the other comprising X2H and X2L in the figure. If the X1H switch is closed while the X1L switch is open, then the left end of the coil is connected to the top node, which is positive. Alternatively, if the X1H switch is open while the X1L switch is closed, then the left end of the coil is connected to the bottom (ground) node. The X2H and X2L switches function similarly. Therefore by closing X1H and X2L (while keeping the other switches open), current flows from left to right through the coil. By closing X2H and X1L, current flows from right to left through the coil. By opening all of the switches, no current flows through the coil.

4 Magnet Placement

Permanent magnets and electromagnets can be arranged in a variety of effective motor configurations. In typical DC (constant voltage) applications, the rotor houses only permanent magnets (to avoid the need to convey electrical power between the rotor and stator). Electromagnets are attached to the stator where they are easily connected to electrical power supplies. As shown by the figure to the right, the rotor (shaded gray) can be configured as a spinning disk that is surrounded by stationary electromagnets or as a spinning ring that surrounds the stationary electromagnets. The inrunner configuration is mechanically simple, since the rotor

![Figure 7](image)

---

1 If the applied voltage varies with time, then electrical power can be transferred between the stator and rotor by induction. Such motors rely on AC (alternating current) power that is supplied by the power grid or more commonly from an electrical circuit called an inverter. AC designs are not considered in this handout.
disk can be directly attached to a central rotating shaft. The outrunner configuration requires a more complicated mechanical connection to the motor shaft, but can offer increased magnetic forces by optimizing the path of the magnetic flux.

The number of permanent magnets and electromagnets and their positioning with respect to each other affect the speed and power of a brushless motor. Consider the simple case in which the rotor contains a single permanent magnet and the stator contains a single electromagnet as shown in Figure 8. In this configuration, the electromagnet generates torque on the rotor in a direction to minimize the distance between the north pole of the rotor and the south pole of the electromagnet (or vice versa).

This same relation between stator excitation of torque can be achieved in a more symmetric configuration shown in Figure 9 where the single permanent magnet and single electromagnet in Figure 8 are replaced by two permanent magnets and two electromagnets. Although the single magnet configuration has fewer parts, the single permanent magnet complicates the design of the motor shaft (which more easily fits between two permanent magnets). The single electromagnet configuration also has the disadvantage that it generates a force on the rotor (in addition to the desired torque) that increases the rotational friction on the motor shaft and tends to cause unwanted vibrations. Finally, although the addition of a second electromagnet increases the number of parts, it also tends to increase torque, which is generally advantageous. For these reasons, we will focus on symmetric designs henceforth.

In order to use the symmetric configuration in Figure 9 as a motor, we need to specify how to energize the electromagnets as a function of rotational angle. We will refer to the rotor angle as zero when the rotor is turned so that its north pole points upward, with positive angles in the clockwise direction and negative angles in the counterclockwise direction. We will refer to the stator excitation as positive when its north pole is up and its south pole is down. With these conventions, positive excitation generates positive (clockwise) torque when the rotor angle is between 0 and $-180$ degrees and negative torque otherwise.

We can implement this rule for operating the motor using a single Hall-effect device as shown by the black rectangle in Figure 10. When the rotor angle is negative (left panel), the sensor is closest to a south pole. We will refer to the resulting sensor voltage as negative. When the rotor angle is positive (right panel), the sensor is closest to a north pole, and the resulting sensor voltage is positive. Thus when the sensor voltage is positive (right panel), negative excitation produces positive torque; and when the sensor voltage is negative (left panel), positive excitation produces positive torque.
Additional permanent magnets and electromagnets can be incorporated to optimize performance parameters such as speed, torque, and smoothness of operation. Figure 11 illustrates a design with six permanent magnets and four electromagnets. The upward arrow indicates that the rotational position of the rotor is zero. In this position the clockwise torque exerted by the red electromagnets is zero (by the left-right symmetry of the rotor) and the clockwise torque exerted by the blue electromagnets is negative, as indicated in the upper plot. Clockwise rotation of the rotor increases the angle and causes the torque from the red electromagnets to go negative, reaching a negative peak at 30 degrees (i.e., when the electromagnet is centered between the north and south poles of adjacent rotor magnets). The torque from the blue electromagnets is at a negative peak when the angle is zero (i.e., the blue electromagnet is centered between the north and south poles of adjacent rotor magnets when the angle is zero) and reaches a positive peak when the rotor has turned 60 degrees. Both the torque exerted by the red electromagnets and by the blue electromagnets are cyclic with a period of 120 degrees. This periodicity is expected since the configuration of rotor magnets is unchanged by 120 degrees of rotation.

There are two Hall-effect devices: A and B. When the angle is zero, the A sensor is halfway between a north and south pole and therefore generates an output of zero (lower plot). As the angle increases, the north pole of the top rotor magnet moves closer to the A sensor, and its output increases, reaching a peak at 30 degrees. The south pole of a rotor magnet is adjacent to the B sensor when the angle is zero, so the output of this sensor starts at a negative peak. As angle increases, the output of the B sensor reaches a peak at 60 degrees. The period of the sensor outputs is the same as that of the torque, again, repeating with the periodicity of the permanent magnet locations on the rotor.

In order to maximize torque, we need to provide negative excitation to the red electromagnets for angles between 0 and 60 degrees and positive excitation for angles between 60 and 120 degrees. Similarly we need to provide positive excitation to the blue electromagnets for angles between 30 and 90 degrees and negative excitation for angles between 90 and 150 degrees. These dependencies are summarized with the following clockwise algorithm:
• If the red sensor output is positive, excite the red electromagnet negatively.
• If the red sensor output is negative, excite the red electromagnet positively.
• If the blue sensor output is positive, excite the blue electromagnet positively.
• If the blue sensor output is negative, excite the blue electromagnet negatively.

For counterclockwise rotation, invert all electromagnet excitations.

5 Physical Layout

Commercially available brushless motors offer a wide variety of performance parameters, including size, speed, torque, and power consumption. They are made with highly optimized manufacturing techniques that allow for customization of magnets, coils, sensors, and switches, as well as integration of all of these parts in compact and sturdy packages.

Here we will focus on rapid prototyping techniques using modern fabrication methods such as laser cutting and 3D printing, and general purpose programmable microcontrollers. While these techniques are not the most efficient for any particular design, they enable a wide range of designs and the ability to revise and remake components of the design with little cost or overhead.

5.1 Electromagnets

We will make our own electromagnets by winding magnet wire in a coil. A typical coil is illustrated in Figure 12. The plastic bobbin is 0.81 inches in diameter and 0.34 inches thick. The approximately 1100 windings are created using 32 gauge magnet wire. Magnet wire is coated with a polymeric varnish as electrical insulation, which must be removed by heat and/or scraping with sandpaper to make electrical connection to its two leads (shown in the upper right part of the figure). The total length of wire is approximately 164’ and has an electrical resistance of approximately 26Ω. When driven with a 5V power supply, this coil generates less than 1W of heat and is mildly warm to the touch.

The electromagnets can be held in place with a machine bolt and an angle bracket as illustrated in Figure 13. In addition to providing mechanical support, the machine bolt also provides a ferrous core through the coil. This core helps to focus the magnetic flux generated by the windings so as to provide greater magnetic forces on the permanent magnets. For example, the design shown in Figure 13 works fine when the coils are held in place by plastic bolts. However, the torque is more than five times greater when steel bolts are used instead.
Electromagnetics can also be wound directly on machine bolts as shown in Figure 14, where flat washers are used to form a bobbin. Non-ferrous washers work best, since a ferrous material tends to spread out the magnetic flux, and thereby reduce the torque produced on the rotor. Metal washers have the additional advantage that they are more heat resistant than plastic. More than a watt of heat can soften and crack the plastic bobbins shown in Figure 12, while as much as three times that can be used with metal structures. Both stainless steel and aluminum washers work well.

5.2 Permanent Magnets

Modern permanent magnets are constructed from rare earth minerals that afford the manufacture of magnets with a wide variety of shapes, sizes, and strengths. Commercial motors use custom fabricated magnets that are inexpensive (per unit) when manufactured in large quantities, but expensive in small quantities. For that reason, we will focus on simple motor designs that can be constructed using cube-shaped permanent magnets that are $\frac{1}{4}$ inch on each side. Made of neodymium, these permanent magnets (Figure 15) are small but powerful, exerting more than 2N of pulling force when brought close to a steel object. Care in handling is important. Neodymium is also brittle and can be cracked by excessive force or impact.

5.3 Rotor

The rotor must be attached to the stator so that it can turn freely. A good way to accomplish this is to attach the rotor rigidly to a motor shaft, and then attach the motor shaft to the stator using ball bearings, so that the shaft can turn freely on the stator. A rigid attachment between the rotor and motor shaft can be obtained by using a D-shaped motor shaft that inserts into a corresponding D-shaped hole in the rotor as shown in Figure 16. The shaft can then be connected to the stator using ball bearings.
**Figure 17** illustrates a cross-sectional view of the resulting assembly. Bearings are inserted into both the top and bottom surfaces of the stator where they are held in place by their flanges. These bearings support the D-shaft which couples rigidly to the rotor. The whole assembly is held together as a sandwich between two collars that attach rigidly to the D-shaft using set screws. Spacers are used to assure that the rotor and lower collar rest on the inner raceway of the bearings, which turns freely with the shaft, rather than the outer raceway, which rests on the stator.

It is important to minimize the distances between the electromagnets in the stator and the permanent magnets in the rotor, because the magnetic interaction forces decrease quickly as the distance. Increasing this distance from 0.2mm to 2mm reduces the magnetic force by more than a factor of 2. **Figure 18** illustrates an example configuration of permanent magnets and electromagnets. The distance from the ferrous core of the electromagnet (a steel bolt) to the permanent magnets is on the order of 3mm (which is substantially larger than comparable distances in a commercial motor).

### 5.4 Connecting Hall-Effect Sensors

An effective way to connect the Hall-effect sensors to the stator is to thread the leads through three small holes in a piece of acrylic as shown in the right part of **Figure 19**. Wires can then be secured to the leads using a wire-wrapping tool as shown in the left part of that figure.

In order to maximize torque, the axis of the electromagnets should line up with the center of the rotor. To maximize the signals from the Hall devices, they should be similarly aligned. One way to accomplish these alignments is illustrated in **Figure 20**. Notice that the rotor has been elevated above the stator to accommodate the coils as well as the leads of the Hall devices.
6 Fabrication

Use Fusion 360 to layout your parts. This program is free to students and can be used to generate 3D printed as well as laser-cut structures.

When designing laser-cut parts, use Fusion’s “sketch” mode.

7 Electronics

To operate the motor, we will program a general purpose microcontroller to continuously monitor the outputs of the Hall-effect sensors and use that information to control the flow of current through the electromagnets.

7.1 Teensy 3.2 Microcontroller

We will use a Teensy 3.2 microcontroller to coordinate sensing and actuation of the motor. The Teensy is a powerful and inexpensive controller that is compatible with Arduino, and is well supported on Linux, Windows, and Macintosh platforms. It is programmed in C/C++, and after programming, it can run standalone or it can be controlled from a laptop using a USB port.

The Teensy has four dedicated pins:

• a power input pin (Vin) which must be connected to a 5V power supply,
• a power output pin (3.3V) which provides power for the Hall-effect sensors and H-bridges,
• an analog ground (AGND) which is the reference voltage for its integrated analog-to-digital converters,
• and a digital ground (GND) which is the reference voltage for the digital logic.

All of the other 24 pins are programmable. Any of these 24 can be used for digital input or output. Any of 10 pins labeled A0 through A9 can be used for analog input or output.
A built-in USB connector provides both power and control signals for the Teensy. When the USB connects to a laptop, the Teensy draws power from the USB port (which ultimately comes from a laptop). While this arrangement is often convenient, it has two drawbacks for the motor project. First, this power is only available when connected to a laptop. Second, and more seriously, the power from the laptop is not generally sufficient to run our motors, which typically require more than 1A of current. For these reasons, we will use external USB power source as shown in Figure 22. Power from this source can be conveniently connected through a second USB connector as shown in the left part of Figure 22.

If we use the same external power supply for both the motor and the Teensy, then we can run the motor without a laptop. We can do this by cutting a tiny trace on the back side of the Teensy as shown in Figure 23. Cutting this trace disconnects power from the laptop while leaving the control signals in place. Since this leaves the Teensy with no power, we must connect the 5V supply from the USB connector shown in Figure 22 to the Teensy Vin. This requires connecting a wire from the pin labeled 5V in Figure 22 to the pin labeled Vin on the Teensy. The ground pins of these circuit boards must also be connected.

7.2 Testing the Power Connection

To avoid damaging your laptop or circuits, test that the laptop USB power is disconnected from the Teensy using the blinker LED provided on the Teensy. Start by testing the Teensy before cutting the trace. Plug the external USB power supply into a new Teensy and then into an AC outlet. The LED on the front surface of the Teensy should blink. Next, cut the trace in Figure 23 and repeat the blink test. This time the LED should not blink because the Teensy should not be receiving power. If the LED blinks, recut the power trace on the backside of the Teensy and repeat this test. If the LED does not turn on, the cutting was successful.
7.3 Connecting Hall-Effect Sensors

As described previously (Figure 19) each Hall-effect sensor requires power to drive electrical current through the magnetic field that we wish to sense. This power is supplied by applying 3.3V to pin 1 (red) relative to ground on pin 2 (black). The resulting Hall-effect voltage is output on pin 3 (blue) relative to ground. The Teensy provides a 3.3V power output (derived from its 5V power input). This 3.3V power supply can be connected directly to each Hall-effect sensor. The output pin of each of the Hall-effect sensors must connect to a separate analog pin (pin A0 to A9) on the Teensy. We will use pin A0 for the first Hall-effect sensor, pin A1 for the second, and so forth in the code that follows.

7.4 H-Bridges for Controlling Electromagnets

The Adafruit TB6612 circuit board provides two H-bridges to control electromagnets. Each H-bridge can supply up to 1.2A at 5V. Multiple electromagnets can share the same H-bridge if they are always switched on and off at the same time. If the coils are connected in series then the same current will flow through each, but only half the available 5V supply voltage will be available to each coil. If the coils are connected in parallel, then each coil will be driven by the same 5V power supply and the total current required from the H-bridge will double.

Each H-bridge (labeled MOTORA and MOTORB) is controlled by two input pins (IN1 and IN2) that configure the switches as shown in Figure 26, where “H” stands for “high” (i.e., 3.3V) and “L” stands for “low” (i.e., digital ground). The unused inputs: PWM and STBY should be connected to 3.3V.

Figure 26 summarizes the electrical connections required to use the TB6612 circuit board. Coil(s) A represents one or more electromagnets that are activated as a unit (as were the two coils shown in Figure 9). These electromagnets are controlled with the AIN1 and AIN2 pins, which can connect to any free pins of the Teensy. Here and in the code that follows, we use pins 0 and 1. Coil(s) B represents a second independent set of electromagnets that are controlled by BIN1 and BIN2 (using, for example, Teensy pins 2 and 3).

The following diagram illustrates the complete wiring diagram for a motor with two independent sets of electromagnets (coil(s) A and coil(s) B) and two Hall-effect devices.
7.5 Wiring

We have provided circuit cards that can be used to control up to four independent coils and four Hall devices using a single Teensy 3.2, as shown below.

Connections to Hall devices and coils are secured with screw terminals. For the Hall sensors, strip 1/4 inch of insulation from each wire. Connect the 3.3 V, ground pins, and Hall sensor pins by turning the screw counterclockwise to loosen, inserting the wire, and then turning the screw clockwise to tighten. The magnet wire for the coils has a polymer varnish insulation. Use very fine sandpaper (600 grit) to remove the insulation from the last inch of each coil lead. After the insulation is removed, trim the stripped part so that only about 1/4 inch has
no insulation. Fasten this stripped part in the screw terminal, making sure that none of the stripped part can touch any other wire or part of the circuit board.

8 Programming

The Teensy3.2 is a powerful and inexpensive controller. It is very similar to Arduino and is supported on Linux, Windows, and Macs. We will use the “Teensyduino” software. Installation of this software is described at https://www.pjrc.com/teensy/td_download.html.

8.1 Teensy Code

The Teensy can be programmed in C/C++ and can be controlled by running code written in any language supported on a laptop host. Our Teensy programs will typically have four parts.

```c
// declarations
...
void setup(){
  // initialization code
  ...
}

void loop(){
  // code to do repeatedly
  ...
}

void serialEvent(){
  // code to process messages to and from laptop
  ...
}
```

We will describe each of these parts in the examples that follow.

8.2 Hall Sensor Code

Reading sensor outputs with Teensy.

```c
// simple program to read output from one Hall device
int HallA = A0; // analog channel for Hall A device
int HallAv; // 0 <= answer < 16384

void setup(){
  analogReadResolution(14); // set A/D converter to 14 bits
}

void loop(){
  HallAv = analogRead(HallA)
}
```
8.3 Coil Control Code

Controlling electromagnets with Teensy.

// simple program to set coil A to north polarity

int coilA1 = 0; // coil A, input pin 1
int coilA2 = 1; // coil A, input pin 2

void setup(){ // setup control pins as Teensy outputs
    pinMode(coilA1,OUTPUT);
    pinMode(coilA2,OUTPUT);
}

void loop() {
    digitalWrite(coilA2,LOW); // turn second control pin off
    digitalWrite(coilA1,HIGH); // then turn first control pin on
}

8.4 Sample Code

int hallA,hallB // 1 if hall sensor is > threshold, 0 otherwise
int oldA,oldB // previous values of halls

void setup(){
    analogReadResolution(14); // set A/D resolution to 14 bits
    pinMode(0,OUTPUT); // use bin 0 or TB6612 Ain1
    pinMode(1,OUTPUT); // use bin 0 or TB6612 Ain2
    pinMode(2,OUTPUT); // use bin 0 or TB6612 Bin1
    pinMode(3,OUTPUT); // use bin 0 or TB6612 Bin2
    oldA = oldB = 2; // initialize previous values to be invalid
}

void off_on(int a,int b){ // turn off TB6612 input a then turn on input b
    digitalWrite(a,LOW); // this order prevents glitches that would
    digitalWrite(b,HIGH); // occur if both inputs were on
}

void loop() {
    hallA = analogRead(A0)>8500; // read hall sensors
    hallB = analogRead(A1)>8500;
    if(hallA!=oldA||hallB!=oldB){ // if either hall sensor changed since last time
        if(hallA) off_on(1,0); else off_on(0,1); // update coil A
        if(hallB) off_on(2,3); else off_on(3,2); // update coil B
        oldA = hallA; // remember old value of hall A
        oldB = hallB; // remember old value of hall B
    }
}
9 Gallery
You have a lot of freedom in designing your motor. Here are some examples from previous years.

9.1 Integrated Electronics
This basic design has electronics built into the base plate. This design eliminates the cable that would otherwise connect the motor and controller card.

9.2 Planar
This planar design has electromagnets built directly into the base plate.
9.3 3D Printed Outrunner

The permanent magnets in an outrunner design lie outside the electromagnets, which are fastened to the base plate. The coil mounts and rotor were 3D printed.

9.4 Laser-Cut Outrunner

This hybrid inrunner/outrunner design has electromagnets both inside and outside a ring of permanent magnets.
9.5 Pancake

This inrunner design as 3D printed and assembled into a flat and sturdy pancake. The electronics are contained inside the 3D printed shell.