Controlling a Brushless Motor
Finish your design and fabrication of parts this week:

- a base plate that supports a motor shaft,
- 1+ electromagnets attached to the base plate to form the stator,
- 1+ Hall-effect sensors attached to the base plate, and
- a rotor with 1+ permanent magnets.

Fabrication tips:

- Laser cut acrylic (1/4”, 1/8”, and/or 1/16”) for planar parts.
- 3D print non-planar parts (but note that 3D printing is slow).
- Our power supplies provide 5V to drive electromagnets
  - limit power to 2 watts per electromagnet to avoid overheating
  - use 32 gauge wire for simple designs with plastic bobbins
- Use **screws** to hold pieces together – **NO glue or tape**
Controlling a Brushless Motor: Example

Rotor angle (degrees)

Sensors: clockwise
Using Hall-Effect to Sensor Rotor Angle

![Diagram showing the use of Hall-Effect sensors to measure rotor angle. The diagram includes a circular arrangement of North and South poles with corresponding sensor points and a graph showing the rotor angle (degrees) varying from 30 to 360 degrees.](image-url)
Using Hall-Effect to Sensor Rotor Angle

rotor angle (degrees)
sensors

30 60 90 120 150 180 210 240 270 300 330 360
Using Hall-Effect to Sensor Rotor Angle

Rotor angle (degrees)

30  60  90  120  150  180  210  240  270  300  330  360

Sensors
Using Hall-Effect to Sensor Rotor Angle

![Diagram showing the relationship between sensor positions and rotor angle](image.png)
Using Hall-Effect to Sensor Rotor Angle

![Diagram showing sensor placement and rotor angle](image-url)
Using Hall-Effect to Sensor Rotor Angle

- The diagram illustrates the use of Hall-Effect sensors to measure the rotor angle.
- The rotor angle is measured in degrees, ranging from 0 to 360 degrees.
- The sensors are placed at specific intervals to detect the rotor's position accurately.

Graph:
- The x-axis represents the rotor angle (degrees) ranging from 30 to 360 degrees.
- The y-axis represents the sensors, indicating the detection points for the rotor angle.
- The graph shows a pattern that repeats every 180 degrees, indicating the periodic nature of the Hall-Effect sensor readings.
Using Hall-Effect to Sensor Rotor Angle

![Diagram showing the relationship between rotor angle and Hall-effect sensors. The diagram includes a circular rotor with North (N) and South (S) poles at regular intervals and a waveform graph below showing the sensor response.](image-url)
If A senses no field, the angle could be 0 or 60 degrees. Add a second sensor to distinguish.
Using Hall-Effect to Sensor Rotor Angle

rotor angle (degrees)

sensors

30  60  90  120  150  180  210  240  270  300  330  360
Using Hall-Effect to Sensor Rotor Angle

![Diagram showing the use of Hall-Effect sensors to measure rotor angle.

The diagram includes a circular pattern with alternating N and S poles, indicating the direction of the magnetic field. A rotor is shown rotating clockwise, with sensors placed at specific intervals along the circumference. The graph below the diagram plots the sensor values against the rotor angle, showing a periodic pattern.

Key points:
1. The rotor angle is measured in degrees.
2. The sensors are labeled and shown in a clockwise rotation.
3. The graph indicates the sensor output for each degree increment.
4. The alternating poles (N and S) suggest a magnetic field orientation.

The diagram effectively demonstrates how Hall-Effect sensors can be used to accurately measure rotor angle in motor systems.
Using Hall-Effect to Sensor Rotor Angle
Using Hall-Effect to Sensor Rotor Angle
Using Hall-Effect to Sensor Rotor Angle

![Diagram showing sensor placement and rotor angle for Hall-Effect sensor usage.](image-url)

- **Sensors**: Blue and red lines indicating sensor output
- **Rotor Angle (degrees)**: Labeled on the horizontal axis
- **Labels**: SNNSNSNSNS (north/south pole labels)
Using Hall-Effect to Sensor Rotor Angle

Rotor angle (degrees)

Sensors
Using Hall-Effect to Sensor Rotor Angle
Using Hall-Effect to Sensor Rotor Angle

Three identical cycles per turn (three-fold symmetry of rotor). Sensor outputs identify unique angle within each cycle.
Characterizing Torque

clockwise torque

rotor angle (degrees)
Characterizing Torque

clockwise torque

rotor angle (degrees)

30 60 90 120 150 180 210 240 270 300 330 360

Characterizing Torque

Clockwise torque

Rotor angle (degrees)
Characterizing Torque

The diagram illustrates the variation of clockwise torque with rotor angle (in degrees) for a rotating machine. The torque peaks and troughs are marked at specific rotor angles, indicating the periodic nature of the torque output as the rotor rotates clockwise.
Characterizing Torque

rotor angle (degrees)
clockwise torque

30 60 90 120 150 180 210 240 270 300 330 360

30 60 90 120 150 180 210 240 270 300 330 360

rotor angle (degrees)
clockwise torque
Characterizing Torque

clockwise torque

rotor angle (degrees)
No torque is produced at multiples of 60 degrees.
Add a second set of electromagnets.
Characterizing Torque

clockwise torque

Rotor angle (degrees)
Characterizing Torque

Rotor angle (degrees):

30  60  90  120  150  180  210  240  270  300  330  360

Clockwise torque

Rotor angle (degrees)

30  60  90  120  150  180  210  240  270  300  330  360
Characterizing Torque

[Diagram showing rotor angle (degrees) from 30 to 360 and clockwise torque with magnetic poles N and S]
Characterizing Torque

erator angle (degrees)

clockwise torque
Characterizing Torque

clockwise torque

rotor angle (degrees)
Characterizing Torque

The diagram shows the relationship between clockwise torque and rotor angle in degrees. The rotor angle increases in a clockwise direction from 0 to 360 degrees. The torque also varies in a periodic manner, with peaks at certain rotor angles.

- Torque peaks at rotor angles of 0, 180, 360 degrees.
- Torque decreases to zero at rotor angles of 90 and 270 degrees.
- The direction of rotation is indicated by the arrow moving clockwise.
Characterizing Torque

Torque vs. Rotor Angle

Clockwise torque

Rotor angle (degrees)
Characterizing Torque

The diagram illustrates the relationship between the clockwise torque and the rotor angle (degrees). The torque values are shown at various rotor angles, indicating a sinusoidal pattern. The diagram also includes North (N) and South (S) magnetic poles to represent the magnetization of the rotor.
Mapping Sensor Readings and Torque Versus Angle

![Diagram showing sensor readings and torque versus rotor angle.](image-url)

- **Sensor Readings:**
  - Clockwise
  - Rotor angle (degrees): 30, 60, 90, 120, 150, 180, 210, 240, 270, 300, 330, 360

- **Torque:**
  - Clockwise
  - Rotor angle (degrees): 30, 60, 90, 120, 150, 180, 210, 240, 270, 300, 330, 360
Teensy 3.2 Microcontroller

The Teensy3.2 is a powerful and inexpensive controller.

Compatible with Arduino, supported on Linux, Windows, and Macs.
Programmable in C/C++. Controllable in any language.

Four dedicated pins:
- two power pins: power in (5V) and power out (3V, 0.1A max)
- two grounds: analog and digital.

24 programmable pins:
- any of these can be used for digital in/out
- 10 pins (A0-A9) can be used for analog in/out
Switches for Electromagnets

Adafruit TB6612 board: 2 H-bridges to control electromagnets.

Each H-bridge can supply up to 1.2A at 5V to one or multiple coils
• connected in parallel (so that currents add) or
• connected in series (so that voltage is divided among them).
External Power Supply

Power for motors is provided from an external microUSB connector.

To use the same source for Teensy (so that motor can run without a laptop) we must disconnect power from the Teeny’s USB port.

Then power comes from external microUSB connector, and USB connector on the Teensy is only used to control the Teensy.
Solder wire-wrap connectors to Teensy, TB6612, and USB boards.

Use wire-wrap to connect power and ground leads as follows.

```
+5V
Vin
+3.3V
Teensy
  gnd
  agnd

+3.3V Vcc
Vm
TB6612
  GND GND GND

+5V
USB
  GND
```
Test Power Wiring

Test power connectors to avoid damage to your laptop or circuits.

**Step 1:** Plug USB power supply into Teensy USB connector and then into wall power. Since we cut the USB power supply, the integrated led shown below **should NOT blink**. If it does, recut the power trace on the backside of the Teensy and repeat this test.

![led blinker](image)

**Step 2:** Remove USB power supply from Teensy USB connector and plug it into the microUSB board. Now the integrated led **should blink**. If it does not, then power is not getting to the Teensy from the microUSB board. Check your power connectors and repeat test.

Do not proceed until you get no blink in step 1 and blink in step 2.
Connecting Hall-effect sensors

Connect Hall-effect sensors.

- **left pin (red):** +3.3V
- **center pin (black):** gnd
- **right pin (blue):** one of Teensy’s analog pins (A0 to A9)

Multiple sensors can share +3.3V and gnd, but each must have a separate analog pin.
Connecting Electromagnets

Each TB6612 board has two H-bridges.

Multiple electromagnets can share the same H-bridge if they are always switched on and off at the same time.
- If connected in series, the voltage across each coil will be halved.
- If connected in parallel, the total current required will double.

Voltage from H-bridge = 5V.
Maximum current from each H-bridge is 1.2A.
Controlling an H-Bridge

Switches in each H-bridge are controlled by input pins: IN1 and IN2.

**OFF**
IN1: L; IN2: L

**BRAKE**
IN1: H; IN2: H

**CW**
IN1: H; IN2: L

**CCW**
IN1: L; IN2: H

\[ H = \text{high} = +3.3\text{V}; \ L = \text{low} = \text{gnd}. \]

Unused inputs: PWM and STBY should be tied H.
Wiring an H-Bridge

Any of the Teensy pins 0 to 23 can be used as a digital control line.

Connect coils to TB6612 using wire-wrapped connections.

Use very fine sandpaper (600 grit) to remove the insulation from the last 2” of magnet wire. To prevent accidental short circuits, wrap 3” of magnet wire (1” with insulation and 2” without) so that ALL of the bare magnet wire is wrapped.
Programming the Teensy 3.2

The Teensy 3.2 is compatible with Arduino.

Use "Teensyduino" software. Installation is described at https://www.pjrc.com/teensy/td_download.html.

Program examples are included in today’s lab.