EECS 192: Mechatronics Design Lab

Discussion 3: Motor Driver and Servo Control

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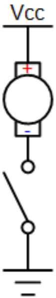
1 & 2 Feb 2017 (Week 3)

- Motor Driver Circuits
- Wiring
- Servomotors
- Summary

Motor Driver Circuits

Single-Transistor Recap (for your reference)

- This simple driver design gives you on/off control while only needing one transistor



Single-transistor driver

Single-Transistor Recap (for your reference)

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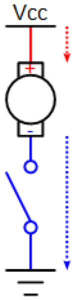
- When the switch is off, no current can flow and the motor freewheels

Motor off

Single-Transistor Recap (for your reference)

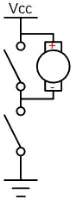
- This simple driver design gives you on/off control while only needing one transistor
- When the switch is off, no current can flow and the motor freewheels
- When the switch is on, current flows through the motor, causing it to spin



Motor on

Half-Bridge Recap (for your reference)

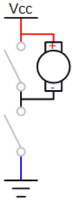
- This driver design gives you drive and braking control using two transistors



Half-bridge driver

Half-Bridge Recap (for your reference)

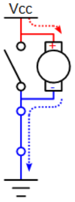
- This driver design gives you drive and braking control using two transistors
- When both switches are off, no current can flow and the motor freewheels



Motor off

Half-Bridge Recap (for your reference)

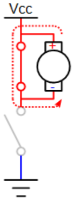
- This driver design gives you drive and braking control using two transistors
- When both switches are off, no current can flow and the motor freewheels
- When the bottom switch is on, current flows through the motor, causing it to spin



Motor on

Half-Bridge Recap (for your reference)

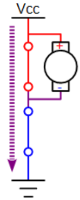
- This driver design gives you drive and braking control using two transistors
- When both switches are off, no current can flow and the motor freewheels
- When the bottom switch is on, current flows through the motor, causing it to spin
- When the top switch is on, the motor's voltage is applied back across itself, applying braking force



Braking

Half-Bridge Recap (for your reference)

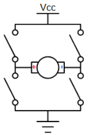
- This driver design gives you drive and braking control using two transistors
- When both switches are off, no current can flow and the motor freewheels
- When the bottom switch is on, current flows through the motor, causing it to spin
- When the top switch is on, the motor's voltage is applied back across itself, applying braking force
- Never turn on both transistors on at once - this shorts the supply across the transistors
  - This condition is called shoot-through



Shoot-through

H-Bridge Recap (for your reference)

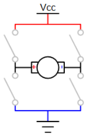
- This driver design gives you forward, reverse, and braking using four transistors



H-bridge driver

H-Bridge Recap (for your reference)

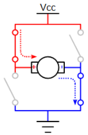
- This driver design gives you forward, reverse, and braking using four transistors
- When all switches are off, no current can flow and the motor freewheels



Motor off

H-Bridge Recap (for your reference)

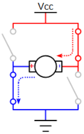
- This driver design gives you forward, reverse, and braking using four transistors
- When all switches are off, no current can flow and the motor freewheels
- With an opposing pair of top and bottom switches on, current flows through the motor causing it to spin



Forward

H-Bridge Recap (for your reference)

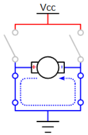
- This driver design gives you forward, reverse, and braking using four transistors
- When all switches are off, no current can flow and the motor freewheels
- With an opposing pair of top and bottom switches on, current flows through the motor causing it to spin
- Turning on the opposite switches causes the motor to spin in the other direction



Reverse

H-Bridge Recap (for your reference)

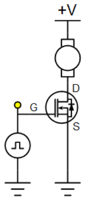
- This driver design gives you forward, reverse, and braking using four transistors
- When all switches are off, no current can flow and the motor freewheels
- With an opposing pair of top and bottom switches on, current flows through the motor causing it to spin
- Turning on the opposite switches causes the motor to spin in the other direction
- Braking is accomplished by turning on both the top or both the bottom switches



Braking

A Single Transistor MOSFET Motor Driver

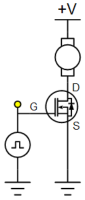
- I've got a demo circuit set up:
  - All running off benchtop power supplies
  - NMOS switch on the low side (source to GND, drain to the motor)
  - Function generator drives MOSFET gate
- A logic-level signal (microcontroller or computer) controls a huge current source (to the motor)
  - Logic pins source around 10 mA; not enough for motors



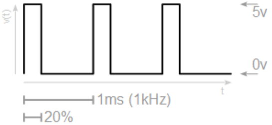
Motor Driver Circuit

PWM Input Waveform

- PWM "interpolates" between on and off
  - Use highly efficient digital switches to approximate analog signal
- Function generator creates a 1kHz PWM signal (square wave) at 20% duty cycle
  - When MOSFET is on, forward current goes through the motor, creating torque
  - When MOSFET is off, no current through the motor, so just spins from inertia
- Do this really fast and you control speed between "full-on" and "full-off"
  - Note that an H-bridge should PWM between forwards and coast or backwards and coast but not forwards and backwards



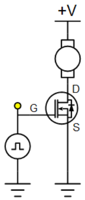
Motor Driver Circuit



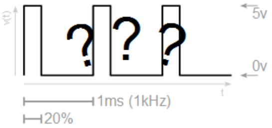
Gate Waveform

Check your Understanding (Live Demo Edition!)

- I can adjust these PWM parameters: frequency (period) and duty cycle
- What should I do to ...
  - ... make the motor faster?
  - ... make the motor slower?
- What happens if ...
  - ... I reduce the frequency?
  - ... I increase the frequency?



Motor Driver Circuit



Gate Waveform

Check your Understanding (Live Demo Edition!)

- I can adjust these PWM parameters: frequency (period) and duty cycle
- What should I do to ...
  - ... make the motor faster?
    - Increase duty cycle (more time in accel)
  - ... make the motor slower?
- What happens if ...
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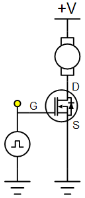
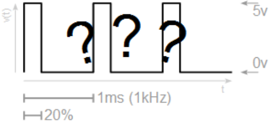
  - ... I increase the frequency?



Motor Driver Circuit



Gate Waveform

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  - ... make the motor slower?
    - Decrease duty cycle (more friction time)
- What happens if ...
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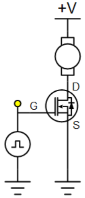
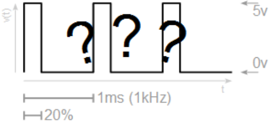
  - ... I increase the frequency?



Motor Driver Circuit



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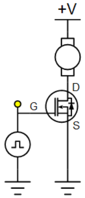
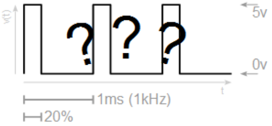
    - Motor chatter, danger of producing high motor currents
  - ... I increase the frequency?



Motor Driver Circuit



Gate Waveform

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- What should I do to ...
  - ... make the motor faster?
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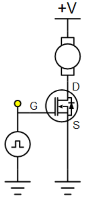
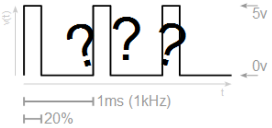
  - ... make the motor slower?
    - Decrease duty cycle (more friction time)
- What happens if ...
  - ... I reduce the frequency?
    - Motor chatter, danger of producing high motor currents
  - ... I increase the frequency?
    - Smoother operation, but thermal effects (switching puts MOSFET through low-efficiency region) and slew



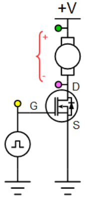
Motor Driver Circuit



Gate Waveform

Sensing speed with back-EMF

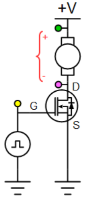
- Recall: a spinning motor produces voltage
  - ... which can be measured to sense speed!
- The scope is connected to the motor leads
  - Green probe on the positive motor lead (connected to the positive supply)
  - Purple probe on the negative motor lead (connected to the MOSFET drain)
- I want the voltage across the motor
  - Use math mode (red) to get green - purple



Back-EMF measurement

Sensing speed with back-EMF

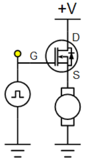
- Recall: a spinning motor produces voltage
  - ... which can be measured to sense speed!
- The scope is connected to the motor leads
  - Green probe on the positive motor lead (connected to the positive supply)
  - Purple probe on the negative motor lead (connected to the MOSFET drain)
- I want the voltage across the motor
  - Use math mode (red) to get green - purple
- ... now what about on a microcontroller?
  - Sample both pins and subtract in software (if sampling speed $\gg$ motor time constant)



Back-EMF measurement

A High-Side Motor Driver

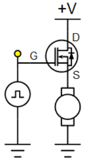
- Consider a MOSFET driving the high side
- What do you think would happen with the same drive waveform at the gate?



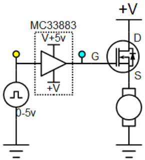
High-side Driver

A High-Side Motor Driver

- Consider a MOSFET driving the high side
- What do you think would happen with the same drive waveform at the gate?
  - Nothing! Insufficient gate voltage!
- Remember: MOSFET on/off depends on voltage between **its** gate and source
  - NOT referenced to the circuit ground
  - But when on, source is at supply voltage
- Must boost gate voltage above the supply
  - Enter the gate predriver chip, MC33883



High-side Driver



With Gate Boost

MC33883 Gate Predriver

- Has four gate drivers:
  - GATE_HSx pins, controlled by IN_HSx
    - Boosts gate above Vcc when on, discharge to SRC_x when off
  - GATE_LSx output controlled by IN_LSx
    - Translates to Vcc when on, discharge to GND when off
    - Generate Vcc-level signals from 3.3v
- Designed to drive H-bridge
  - No shoot-through logic protection
  - Can be used as 4 independent drivers
  - Can use the GATE_HSx to apply higher gate voltage to low-side FETs

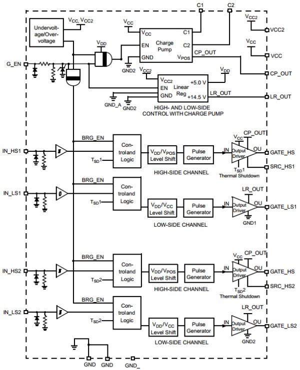


Figure 2. 33883 Simplified Internal Block Diagram

MC33883 Functional Block

source: MC33883 datasheet, by Freescale

MC33883 Misc Tips (for your reference)

Important specs from the datasheet

- Minimum Vcc, Vcc2 of 5.5v
  - and a maximum Vcc of 55v, Vcc2 of 28v
- G_EN pin as gate enable, set low to disable, set >4.5v to enable
  - 3.3v logic-level drive will NOT work!
- At Vcc=7.2v (maximum for Freescale Cup), charge pump output Vcp≈12v
  - Which is ∼4.5v over Vcc, sufficient to drive a high-side MOSFET
- 3.3v logic comptible input ports
  - Anything above 2.0v treated as high
  - Anything below 0.8v treated as low
- Maximum PWM frequency of 100kHz

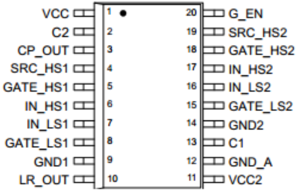


Figure 3. 33883 20-SOICW Pin Connections

and the all-important Pinning Diagram

source: MC33883 datasheet, by Freescale

MC33883 Application Circuit (for your reference)

Datasheet page 18 has all you need to know

You can skip the Zener diodes and use independent MOSFETs, but make sure to tie SRC_x to the MOSFET source of GATE_HSx

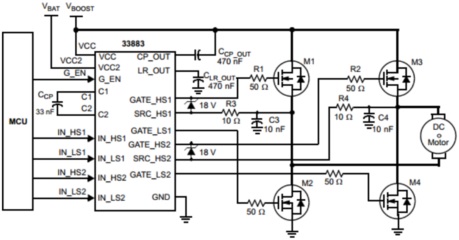


Figure 14. Application Schematic with External Protection Circuit

MC33883 Application Circuit

source: MC33883 datasheet, by Freescale

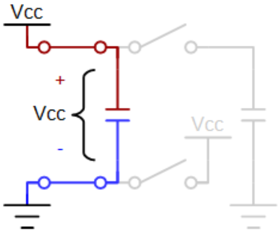
Charge Pump Theory (for your reference)

So, how does the MC33883 generate gate voltages above Vcc?

- Uses a switched-capacitor charge pump

Let's start with a simple switched-capacitor voltage doubler circut...

- Start by charging capacitor to Vcc



Capacitor charging

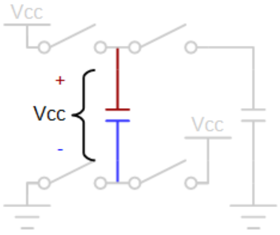
Charge Pump Theory (for your reference)

So, how does the MC33883 generate gate voltages above Vcc?

- Uses a switched-capacitor charge pump

Let's start with a simple switched-capacitor voltage doubler circut...

- Start by charging capacitor to Vcc
- Disconnect capacitor from supplies
  - Capacitor retains its charge



Capacitor floating

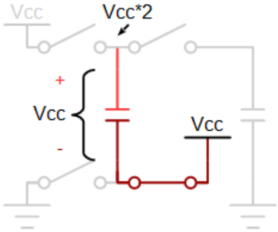
Charge Pump Theory (for your reference)

So, how does the MC33883 generate gate voltages above Vcc?

- Uses a switched-capacitor charge pump

Let's start with a simple switched-capacitor voltage doubler circut...

- Start by charging capacitor to Vcc
- Disconnect capacitor from supplies
  - Capacitor retains its charge
- Connect capacitor low-side to Vcc
  - Capacitor high-side now at 2Vcc



Voltage doubled

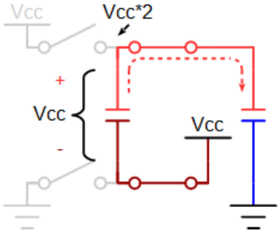
Charge Pump Theory (for your reference)

So, how does the MC33883 generate gate voltages above Vcc?

- Uses a switched-capacitor charge pump

Let's start with a simple switched-capacitor voltage doubler circut...

- Start by charging capacitor to Vcc
- Disconnect capacitor from supplies
  - Capacitor retains its charge
- Connect capacitor low-side to Vcc
  - Capacitor high-side now at 2Vcc
- Connect capacitor to output filter
  - Charge output filter to 2Vcc

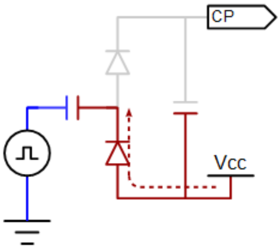


Charge output

MC33883 Charge Pump (for your reference)

MC33883's charge pump uses an oscillator and diodes instead of switches

- When oscillator is low, capacitor is charged through diode

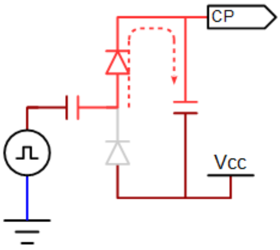


Capacitor charging

MC33883 Charge Pump (for your reference)

MC33883's charge pump uses an oscillator and diodes instead of switches

- When oscillator is low, capacitor is charged through diode
- When oscillator goes high, low-side of capacitor goes to Vcc
  - High side of capacitor rises as well and charges CP through the diode
- (this illustrates the concept but skips details like different voltages and diodes)



Charge output

Questions?

got it?

ready to pwn checkpoint 3?

Wiring

Wire Gauge

- American Wire Gauge (AWG) standardized sizing
- Copper's resistance is 1.72e-8 Ω m
- How do you compute resistance?

AWG	Diam mm	Sect. mm²	Resist. ohm/m	AWG	Diam mm	Sect. mm²	Resist. ohm/m
0000	11.7	107,0	0.000161	19	0,91	0,6530	0.0264
000	10.4	85.0	0.000203	20	0,81	0,5190	0.0333
00	9.26	67.4	0.000256	21	0,72	0,4120	0.0420
0	8.25	53.5	0.000323	22	0,64	0,3250	0.0530
1	7,35	42,4	0.000407	23	0,57	0,2590	0.0668
2	6,54	33,6	0.000513	24	0,51	0,2050	0.0842
3	5,83	26,7	0.000647	25	0,45	0,1630	0.106
4	5,19	21,2	0.000815	26	0,40	0,1280	0.134
5	4,62	16,8	0.00103	27	0,36	0,1020	0.169
6	4,11	13,3	0.00130	28	0,32	0,0804	0.213
7	3,67	10,6	0.00163	29	0,29	0,0646	0.268
8	3,26	8,35	0.00206	30	0,25	0,0503	0.339
9	2,91	6,62	0.00260	31	0,23	0,0415	0.427
10	2,59	5,27	0.00328	32	0,20	0,0314	0.538
11	2,30	4,15	0.00413	33	0,18	0,0254	0.679
12	2,05	3,31	0.00521	34	0,16	0,0201	0.856
13	1,83	2,63	0.00657	35	0,14	0,0154	1.08
14	1,63	2,08	0.00829	36	0,13	0,0133	1.36
15	1,45	1,65	0.0104	37	0,11	0,0095	1.72
16	1,29	1,31	0.0132	38	0,10	0,0078	2.16
17	1,15	1,04	0.0166	39	0,09	0,0064	2.73
18	1,02	0,82	0.0210	40	0,08	0,0050	3.44

AWG Table

source: moddiy.com

Wire Gauge

- American Wire Gauge (AWG) standardized sizing
- Copper's resistance is 1.72e-8 Ω m
- How do you compute resistance?
  - Look up AWG diameter
  - $R = \frac{1.72e{-}8}{\pi r^2} l$

AWG	Diam mm	Sect. mm^2	Resist. ohm/m	AWG	Diam mm	Sect. mm^2	Resist. ohm/m
0000	11.7	107,0	0.000161	19	0,91	0,6530	0.0264
000	10.4	85.0	0.000203	20	0,81	0,5190	0.0333
00	9.26	67.4	0.000256	21	0,72	0,4120	0.0420
0	8.25	53.5	0.000323	22	0,64	0,3250	0.0530
1	7,35	42,4	0.000407	23	0,57	0,2590	0.0668
2	6,54	33,6	0.000513	24	0,51	0,2050	0.0842
3	5,83	26,7	0.000647	25	0,45	0,1630	0.106
4	5,19	21,2	0.000815	26	0,40	0,1280	0.134
5	4,62	16,8	0.00103	27	0,36	0,1020	0.169
6	4,11	13,3	0.00130	28	0,32	0,0804	0.213
7	3,67	10,6	0.00163	29	0,29	0,0646	0.268
8	3,26	8,35	0.00206	30	0,25	0,0503	0.339
9	2,91	6,62	0.00260	31	0,23	0,0415	0.427
10	2,59	5,27	0.00328	32	0,20	0,0314	0.538
11	2,30	4,15	0.00413	33	0,18	0,0254	0.679
12	2,05	3,31	0.00521	34	0,16	0,0201	0.856
13	1,83	2,63	0.00657	35	0,14	0,0154	1.08
14	1,63	2,08	0.00829	36	0,13	0,0133	1.36
15	1,45	1,65	0.0104	37	0,11	0,0095	1.72
16	1,29	1,31	0.0132	38	0,10	0,0078	2.16
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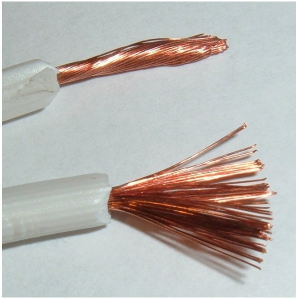
18	1,02	0,82	0.0210	40	0,08	0,0050	3.44

AWG Table

source: moddiy.com

Wire Types

- Solid
  - A single solid chunk of copper conductor
  - Rigid but inflexible: helpful in some cases
- Stranded
  - Several thin strands bundled together
  - More flexible, especially when there are more (that is thinner) strands
- Wire gauge (size) is by cross-section area
  - Equivalent stranded wire is "thicker" because of space between strands
- Which resists breaking from flexing? Why?



Stranded Wire

source: Wikipedia, Scott Ehardt

Wire Types

- Solid
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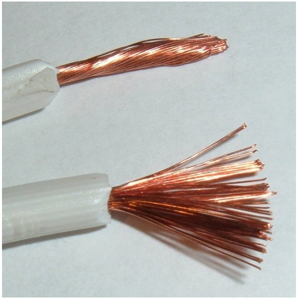
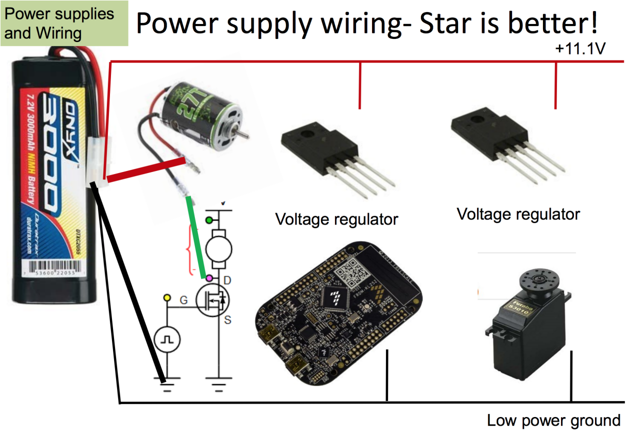
  - Equivalent stranded wire is “thicker” because of space between strands
- Which resists breaking from flexing? Why?
  - Stranded wire: thinner strands experience lower bending stress



Stranded Wire

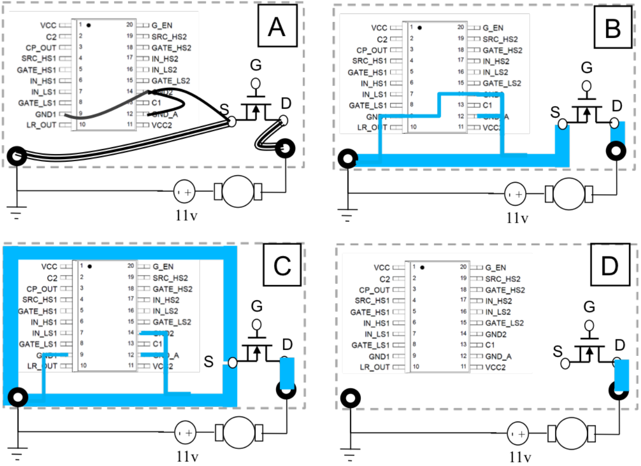
source: Wikipedia, Scott Ehardt

Wiring Topology



Do not create ground loops!

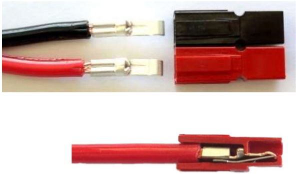
Bad Wiring: “Why is my MC3383 Dead?”



What would be better?

Anderson Powerpole

- Physically and electrically hermaphroditic
  - Physically can't insert it the wrong way
  - Both sides of the connector are identical
- We're standardizing on the PP15/30/45
  - 15-amp contacts suitable for 16-20 AWG wire
  - 30-amp contacts for larger (12-14 AWG) wire
- Complete set of tools available
  - Crimper and insertion tool
- Use this for all your high-power connectors
  - Battery to board, driver to motor, ...
- Quick demo



Powerpole Connector

source: Wikipedia, Cqdx

Questions?

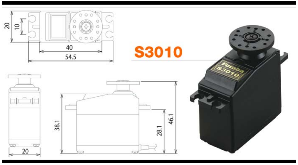
makes sense?

tl;dr: use stranded wire

Servomotors

Intro

- Servomechanism: device using feedback loop to provide control
- RC cars use servomotor-actuated steering
  - Motor senses output shaft position and adjusts to hit commanded angle
  - Freescale Cup allows the Futaba S3010
- 3-wire standard servo cable:
  - white / yellow / orange: signal
  - red: positive supply voltage
  - black / brown: ground

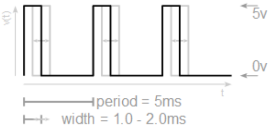


S3010 Servomotor

source: Futaba, www.futaba-rc.com

PWM Control

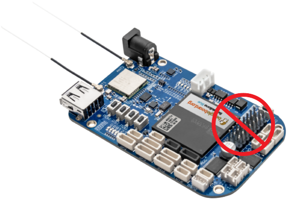
- NOT the same PWM as motor control
- Servo setpoint by width of high pulse
  - Allowable width between 1ms - 2ms
  - 1.5ms to set setpoint to center
- Servo expects regular pulses
  - Cheap/old servos expect 50 Hz, fancy ones can run up to 400 Hz
  - Servo will timeout (and turn off) if it doesn't get regular data



PWM Waveform

DO NOT USE BBBL SERVO PINS

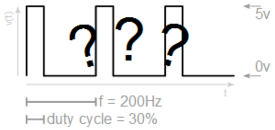
- The Beaglebone Blue has enticingly convenient servo pins ...
- Do not be fooled! Do NOT plug the servo into them!
- The 6V rail cannot source enough current for our beefy steering servos.
- Use only the signal line, not the power or ground rails.



PWM Waveform

Check your Understanding (Live Demo Edition!)

- I have a function generator PWM set at Vpp=5v, Vdc=2.5v, f=200 Hz, 30% duty
- What is the period and pulse width?
- What will the setpoint be?
- What do I do to move it towards one side?



PWM Waveform

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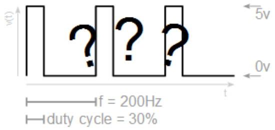

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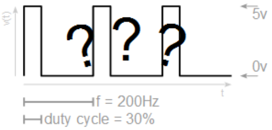
- What will the setpoint be?
  - Dead center
- What do I do to move it towards one side?



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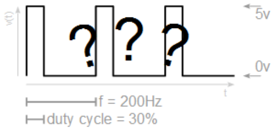
  - period=5ms, pulse width=1.5ms
- What will the setpoint be?
  - Dead center
- What do I do to move it towards one side?
  - Adjust the duty cycle, say, downwards



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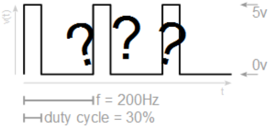
  - period=5ms, pulse width=1.5ms
- What will the setpoint be?
  - Dead center
- What do I do to move it towards one side?
  - Adjust the duty cycle, say, downwards
  - Beware of mechanical blockage stalling!



PWM Waveform

Questions?

got this down?

we all know how to steer now, right?

Summary

Summary

- Apply PWM waveform to motor driver circuits to control speed
- Use a gate predriver to drive MOSFETs from wimpy 3.3v logic
- Steering servos controlled with a different kind of PWM
- Use stranded wire

Parts Handout

- 4 IRFB3006PBF MOSFETs
- Perfboard
- SOIC carriers and MC33883 chips
- Need help soldering SOIC? Come to office hours!