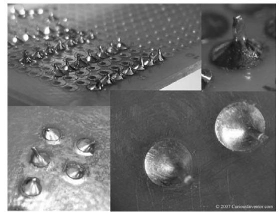
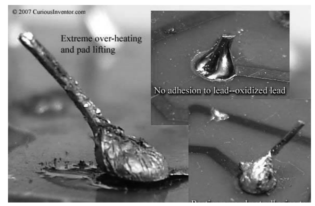
Soldering Basics

- Clean area
- Pre-tin wires and tip
- Clamp your work
- Apply heat to the wire and the pad
- Add solder to the part not the iron
- Apply for ~ 5 sec.
  - Should wet part and pad clearly
- Clear the flux residue



Good !



BAD !

Review this:

http://store.curiousinventor.com/guides/how_to_solder/

Review of Preliminaries - Soldering

Steps necessary for good soldering:

- Clean working area (if necessary)
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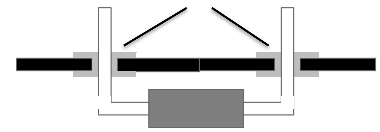

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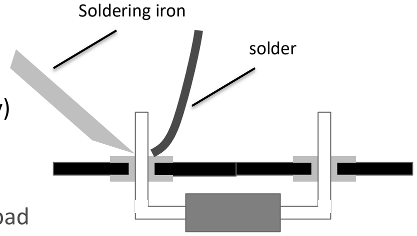

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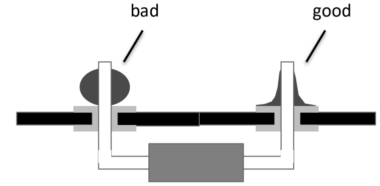
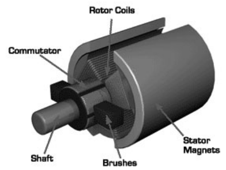
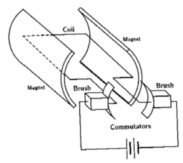


DC Motors

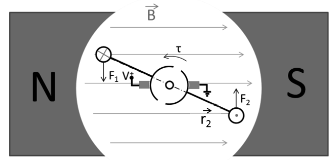
- Use to provide a torque to a shaft, capable of spinning the shaft to some velocity under the application of a DC current



http://www.electrical4u.com/permanent-magnet-dc-motor-or-pmdc-motor/



http://mechatronics.mech.northwestern.edu/design_ref/actuators/motor_theory.html



$$\vec{F} = i\vec{l} \times \vec{B}$$
$$\tau = \vec{r}_1 \times \vec{F}_1 + \vec{r}_2 \times \vec{F}_2$$

DC Motors

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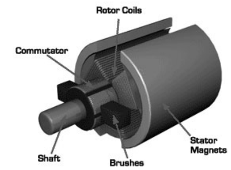

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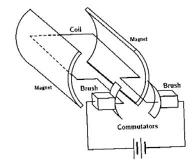

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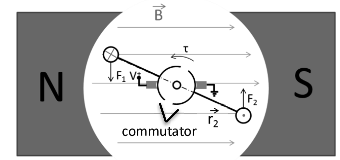

$$\vec{F} = i\vec{l} \times \vec{B}$$
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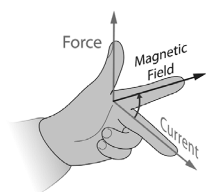
Lorenz Law

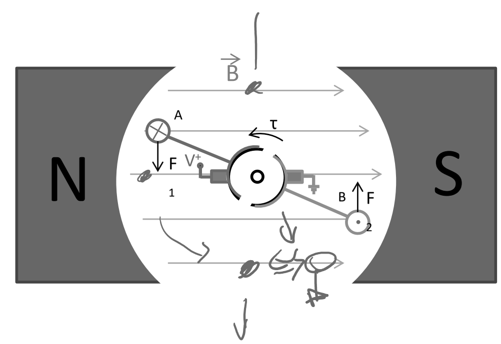
Fleming's left-hand rule for motors

- Left index finger is pointing in the direction of the magnetic field vector
- Left middle finger points in the direction of the current vector
- Thumb indicates the direction of the force



http://www.bigshotcamera.com/fun/buildables/motor#01

DC Motors: commutator



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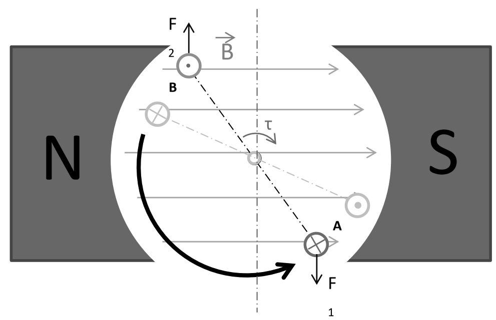
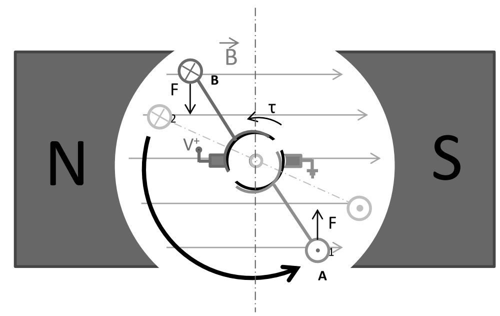
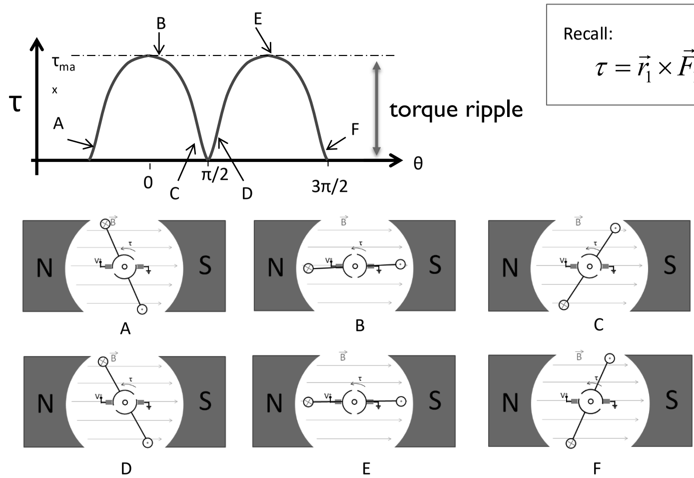


DC Motors: commutator



DC Motors: torque ripple

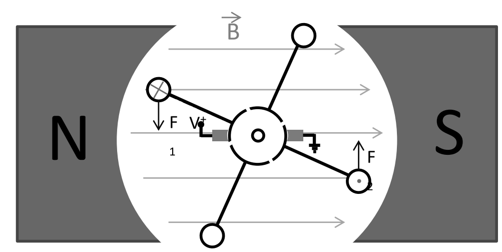


Recall:

$$\tau = \vec{r}_1 \times \vec{F}_1 + \vec{r}_2 \times \vec{F}_2$$

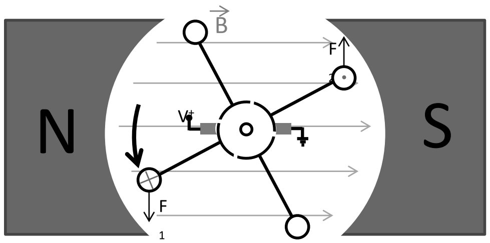
DC Motors: torque ripple

- 4-segment commutator:



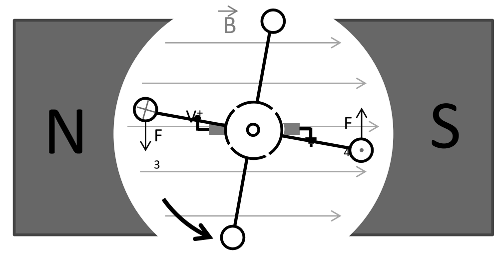
DC Motors: torque ripple

- 4-segment commutator:



DC Motors: torque ripple

- 4-segment commutator:



DC Motors: torque ripple

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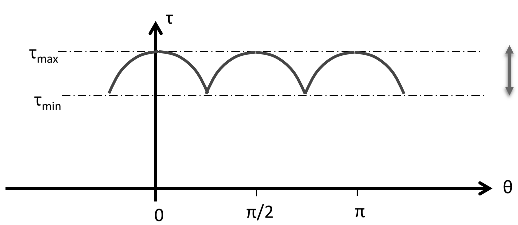
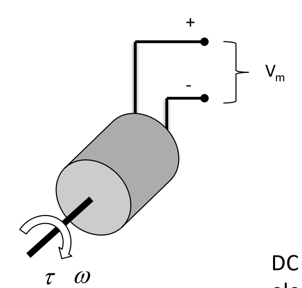
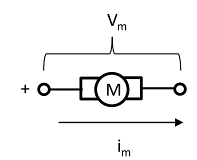


Now, greatly reduced torque ripple

Motor: Electrical Equivalent Circuit



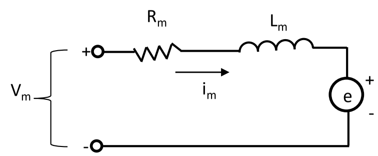
Symbol:



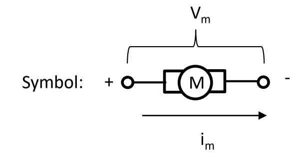
DC motor can be represented as an electrical element in a circuit diagram:

- V_m is the across element voltage (motor voltage)
- i_m is the through element current (motor current)

Motor: Electrical Equivalent Circuit



$V_{emf} = k_e\omega$



$\tau = k_t i_m$ $\quad V_m = k_e\omega + i_m R_m$ ⟵ Assumes $\frac{di_m}{dt} \approx 0$

An equivalent circuit can be constructed to model the operation of the motor from an electrical perspective.

Lorenz Law

Fleming's left-hand rule for motors

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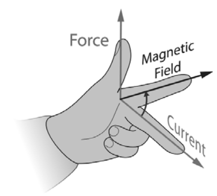
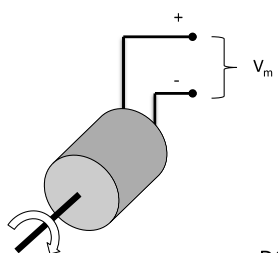
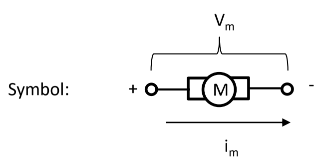


http://www.bigshotcamera.com/fun/buildables/motor#01

Motor: Electrical Equivalent Circuit





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- V_m is the across element voltage (motor voltage)
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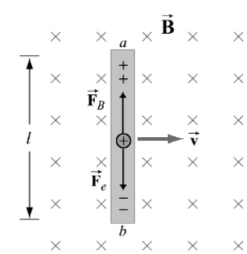
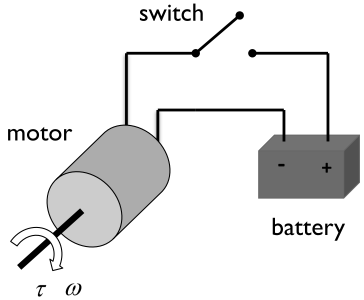
Electromotive Force in a Wire moving through B-field

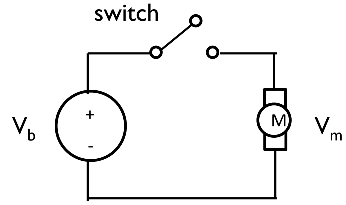
Electrons in a w A wire moving through a magnetic field B at a velocity v will be pushed towards one end, while the holes will be pushed to the other end, causing a net potential V_{emf}



http://web.mit.edu/8.02t/www/materials/StudyGuide/guide10.pdf

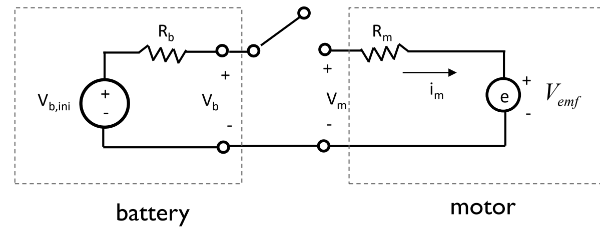
Motor: Electrical Equivalent Circuit





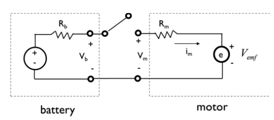
The DC motor connected to the battery with a switch in between.

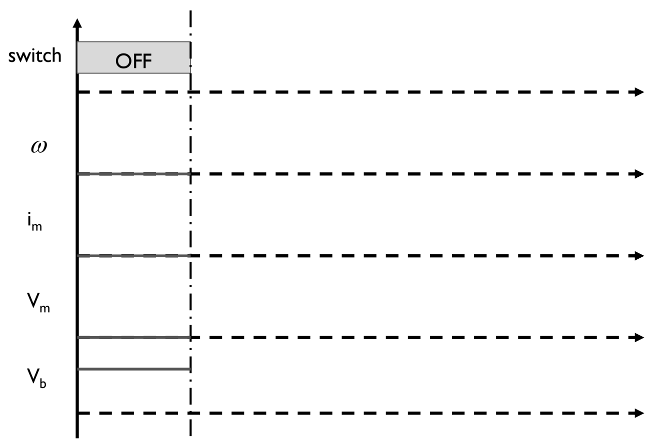
Motor: Electrical Equivalent Circuit



Combined equivalent circuit diagram for the simple battery – motor system.

Motor: Electrical Equivalent Circuit Analysis





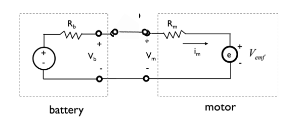
Motor at rest $\omega = 0$

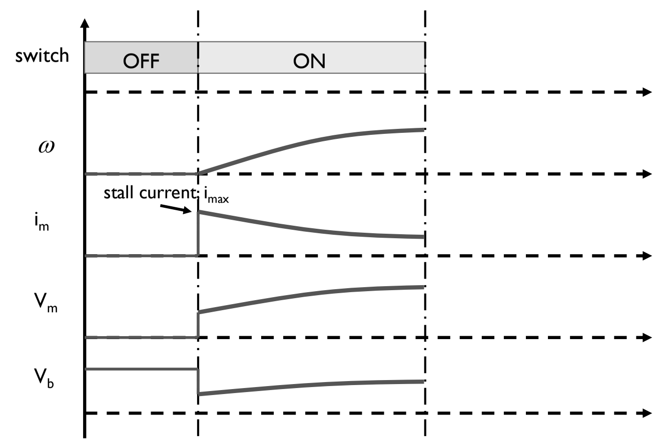
Motor current zero

Motor voltage zero

Nominal (open circuit) battery voltage V_b

Motor: Electrical Equivalent Circuit Analysis





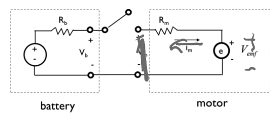
Motor spinning up
ω is increasing.

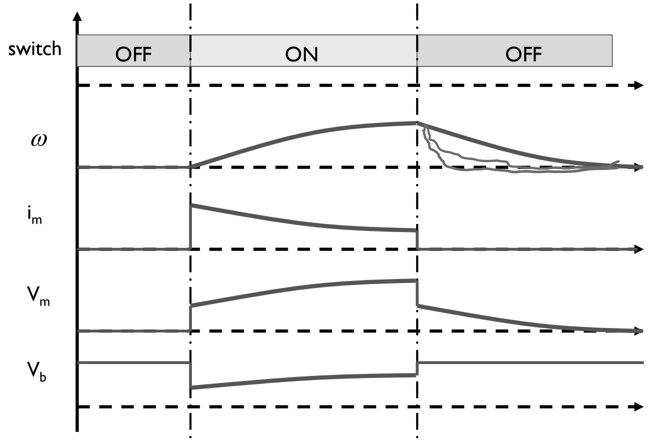
Motor current initially sharply increases, but then starts dropping due to V_{emf}

Motor voltage jumps up, and slowly keeps increasing due to buildup of V_{emf}

Sharp increase in i_m causes voltage drop across R_b, and drop in V_b. As i_m is reduced, V_b increases.

Motor: Electrical Equivalent Circuit Analysis





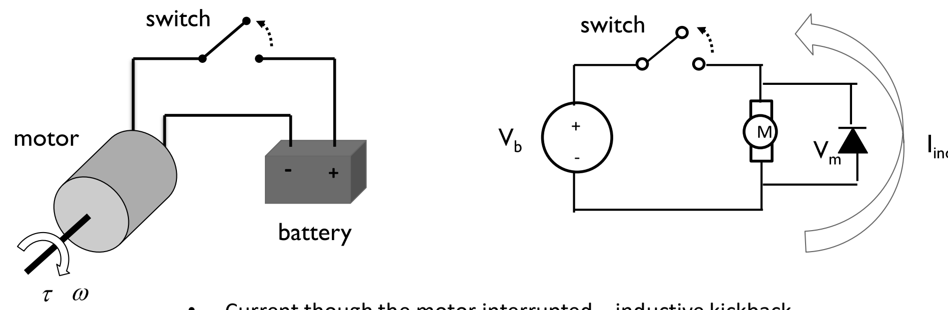
Motor spinning down ω is increasing.

Motor current drops to zero

Motor voltage drops down to the value provided by only V_{emf}

V_b goes up to $V_{b,ini}$, as no voltage drop over R_b

Motor: Inductive Kickback

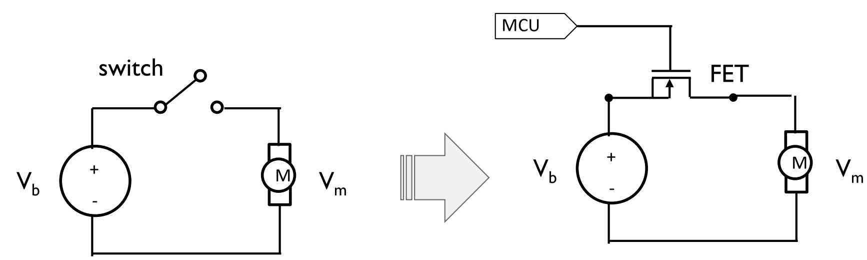


- Current though the motor interrupted – inductive kickback
- Reversed-biased snubber diodes short the resulting voltage spike

Summary: DC Motors

- DC Motors provide actuation for many mechatronic systems such as electric cars
- A commutator ensures that the torque spins the shaft in one direction for a certain polarity
- Back EMF generates a voltage across the winding, limiting the motor current, as a function of the angular velocity of the shaft (and winding)
- Two important implications of back EMF:
  - It will limit the ultimate angular velocity of the shaft (if it didn't all unloaded DC motors would likely disintegrate: $\omega \rightarrow \infty$)
  - Can be used for velocity sensing
  - Highest motor current at stall ($\omega = 0$). Motor controllers *must* be designed to handle stall currents
- Snubber diodes help to remove voltage spikes due to switching current through the winding

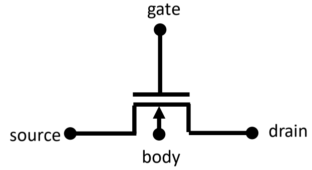
Motor Controllers



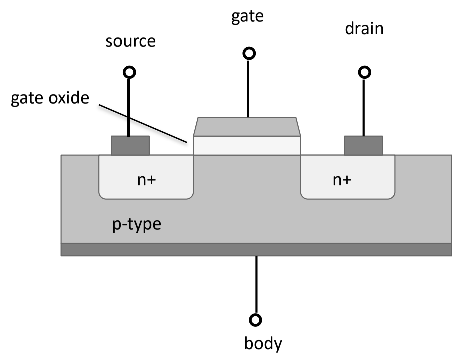
- Motor controller is an amplifier which converts the weak signals from microcontroller GPIO ports to high current that drive the motor.
- Solid-state using Power FET technology (e.g. NDP7060L)
  - Fast switching time
  - Large currents

Field Effect Transistor: A Review

- Can be n-channel or p-channel
  - Most common n-chanel
- Fabricated on a doped silicon substrate
- Has four terminals: Source, Drain, Gate, and Body.
  - If not specified, body is assumed connected to Source



Symbol

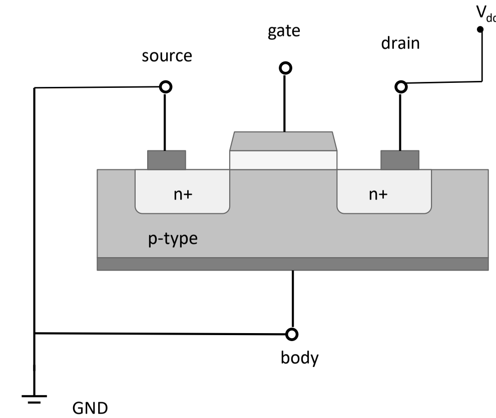


Cross-section of an n-type (n-channel) FET

Field Effect Transistor: A Review

FET Operation (n-channel)

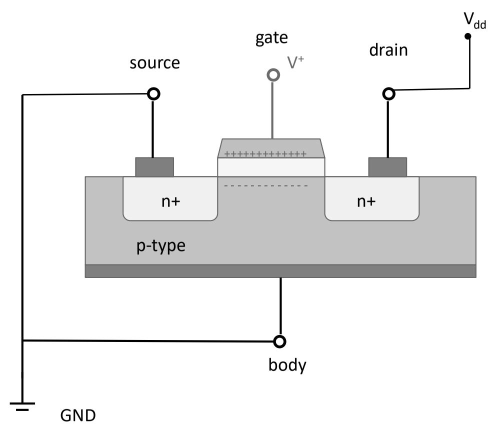
- source/body is usually connected to ground
- drain is connected to V_{dd}
- Initially source and drain isolated through a dual PN junction



Field Effect Transistor: A Review

FET Operation (n-channel)

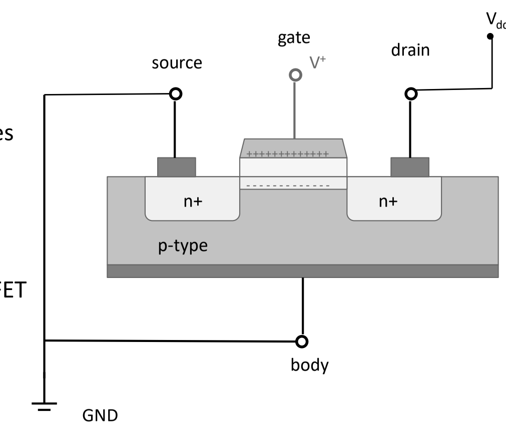
- To switch transistor on, gate is connected to positive voltage
- Accumulation of **positive** charges on the gate electrode attracts **negative** charges just underneath the gate, in the channel region



Field Effect Transistor: A Review

FET Operation (n-channel)

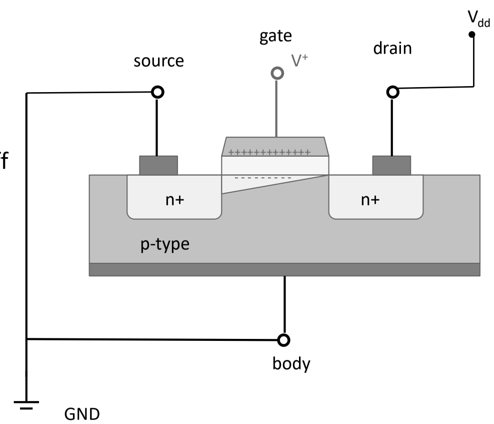
- When the density of negative charges in the channel reaches a certain threshold, the channel becomes conductive
  - Above gate threshold voltage
- Initially, channel acts like a resistor, FET operates in the **linear region**



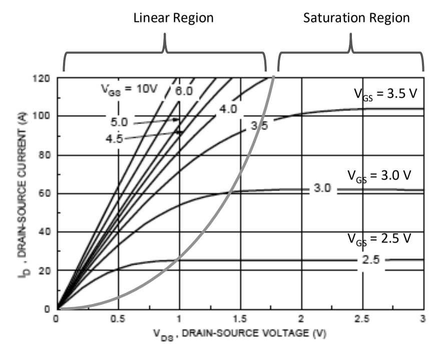
Field Effect Transistor: A Review

FET Operation (n-channel)

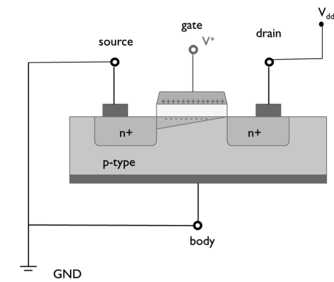
- As drain to source voltage (V_{ds}) increases, the channel gets pinched off at the drain, limiting the drain to source current (i_{ds})
- FET is now operating in the **saturation region**



Field Effect Transistor: A Review



I/V characteristics for a NDP7060L Power FET



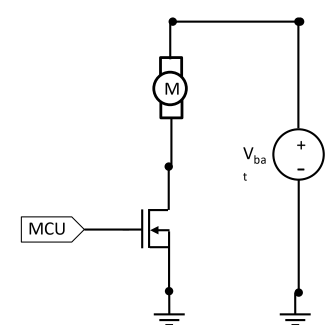
Datasheet NDP7060L

Summary: Field Effect Transistors

- Power FETs are used as solid state switches in a motor controller
- In an n-channel FET, positive charges on the gate form a n-type channel between the source and the drain
- Once on, a FET operates in either linear or saturated region

Motor Controllers: FETS as switches

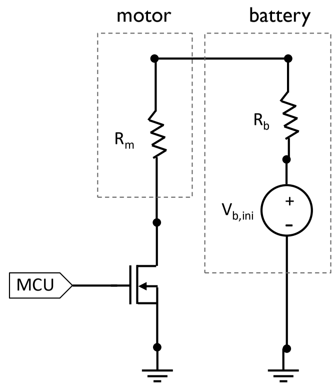
- Switch is now replaced with a FET
- Single FET motor controller
  - Only turn in one direction
- Motor and battery resistance in series
  - Analyze for maximum (i.e. stall) current



single transistor controller

Motor Controllers: FETS as switches

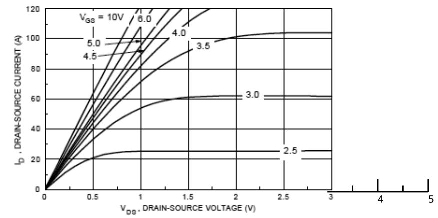
- Modify electric diagram for stall ($\omega = 0$)
  - No back EMF
  - No inductive component
- Load-line analysis



single transistor controller

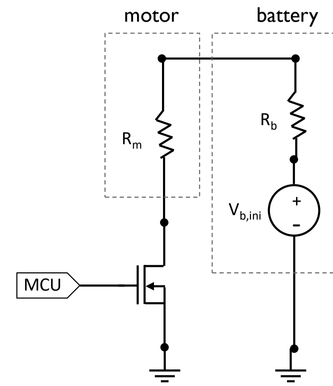
Motor Controllers: FETS as switches

- E.g. assume
  - $V_{b,ini} = 5$ V, $R_m = 0.06\ \Omega$, $R_b = 0.01\ \Omega$
  - V_{gs} provided by the MCU



I/V characteristics for a NDP7060L Power FET

Datasheet NDP7060L



single transistor controller

Motor Controllers: FETS as switches

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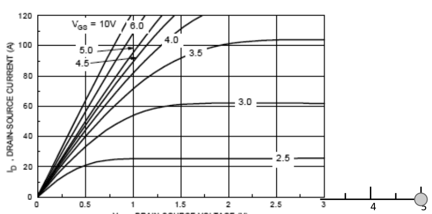
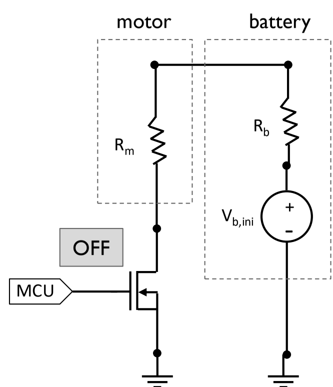


I/V characteristics for a NDP7060L Power FET

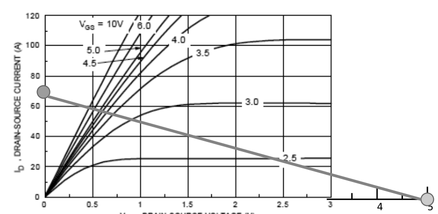
Datasheet NDP7060L



single transistor controller

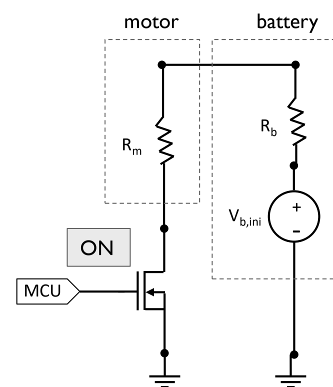
Motor Controllers: FETS as switches

- E.g. assume
  - $V_{b,ini} = 5$ V, $R_m = 0.06\ \Omega$, $R_b = 0.01\ \Omega$
  - V_{gs} provided by the MCU



I/V characteristics for a NDP7060L Power FET

Datasheet NDP7060L



single transistor controller

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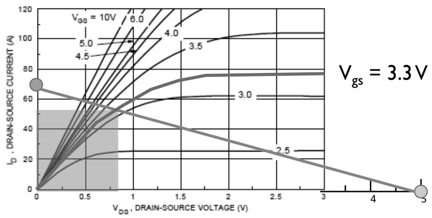

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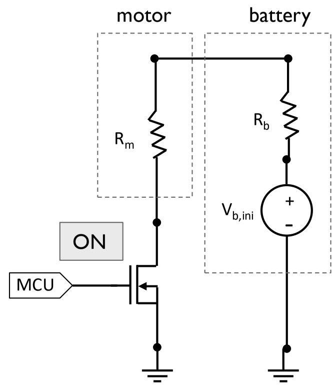

single transistor controller

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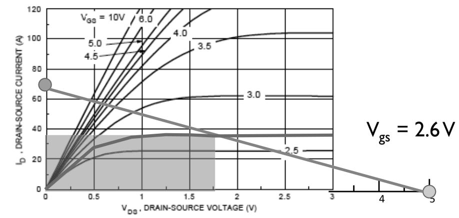

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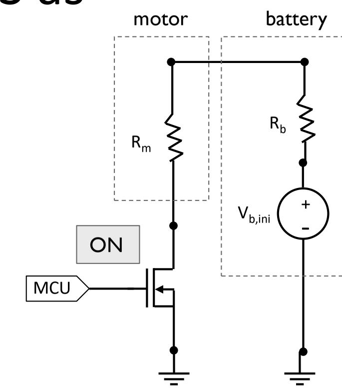

single transistor controller

Motor Controllers: the need for FET drivers

- To reduce the power dissipation in ON state, V_{gs} must be as high as possible (up to gate voltage breakdown)
  - V_{gs} may be above V_{dd}
- 3.3 V output from GPIO not high enough

- Solution: FET Drivers
  - Solid-state circuits that elevate ON output voltage to a higher ON level.
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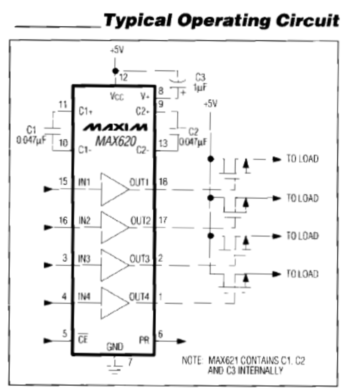
  - E.g. MAX 621elevates ON output voltage by 11 V *above* V_{dd}.



Datasheet MAX620/621

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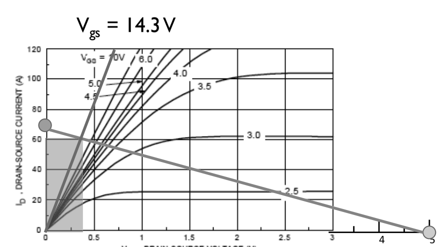

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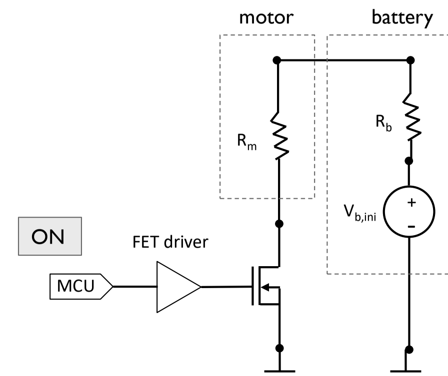


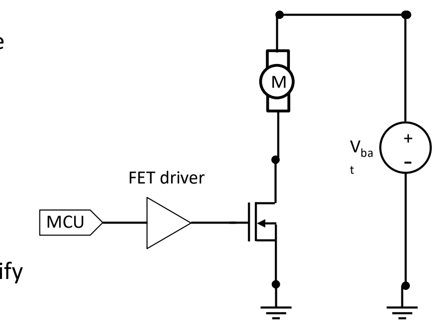
single transistor controller

Summary: Motor Controllers

- Motor controllers are used to control the actuation of a motor using one or more FETs
- Load-line analysis is used to determine power dissipated in a FET in a motor controller
- To lower dissipated power in FET, V_{gs} needs to be as high as possible
- A FET driver is used to elevate V_{gs} above V_{dd}ensuring proper switching

Motor Controllers Topologies

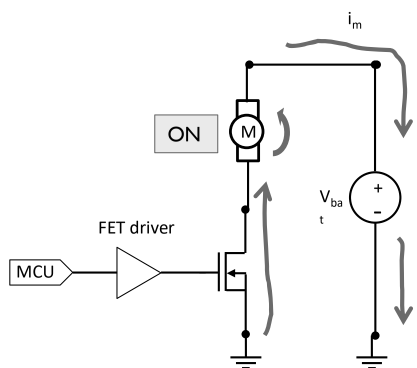
- Single FET motor controllers have the simplest topology
  - Can only accelerate, and coast to stop
- Other topologies allow for:
  - Breaking
  - Backwards motion
- Most common, full H-bridge
- Possible to use a half-bridge to simplify the controller design



single transistor controller

Motor Controllers Topology: Single FET

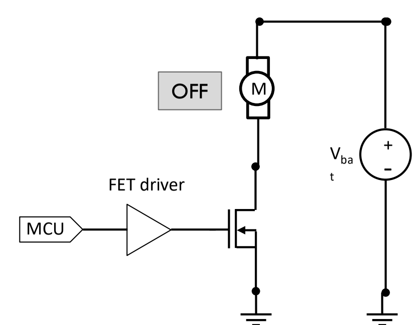
- FET ON
  - Accelerates



single transistor controller

Motor Controllers Topology: Single FET

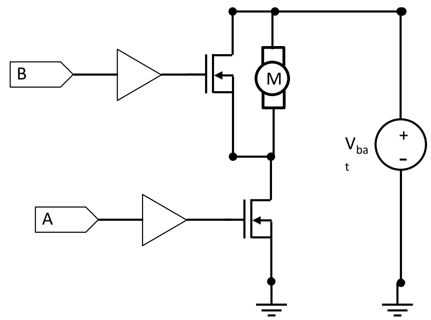
- FET OFF
  - Coasts (open connectors) to stop



single transistor controller

Motor Controllers Topology: Half-Bridge

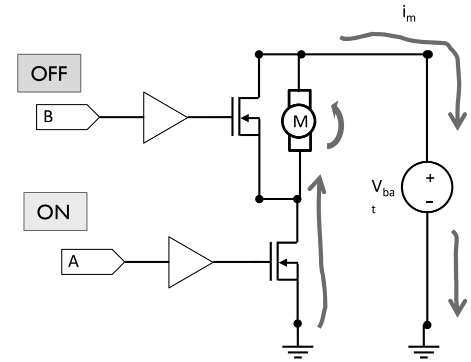
- It is possible to accelerate breaking by use the concept of **dynamic breaking**
- The V_{emf} generated by the motor is used to drive current through armature to cause breaking of the motor
- Required additional FET



Half-bridge

Motor Controllers Topology: Half-Bridge

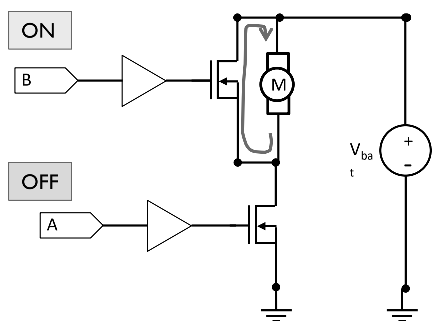
- Accelerate:
  – A ON, B OFF



Half-bridge

Motor Controllers Topology: Half-Bridge

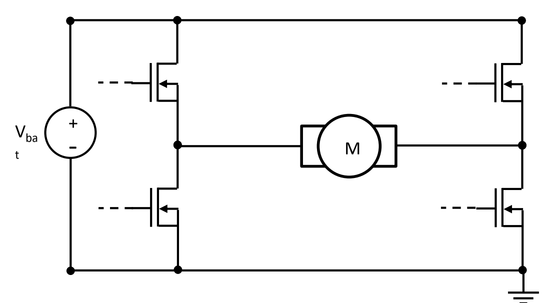
- Dynamic Breaking:
  – A OFF, B ON



Half-bridge

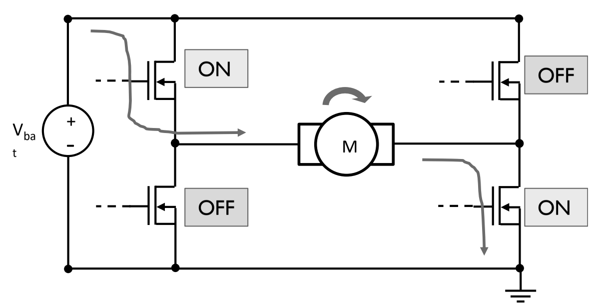
Motor Controllers Topology – H-Bridge

- The most versatile motor controller topology is an H-bridge
- Requires four (4) FETs per motor



Motor Controllers Topology – H-Bridge

- The most versatile motor controller topology
- Requires four (4) FETs per motor
- Supports:
  - Motion forward



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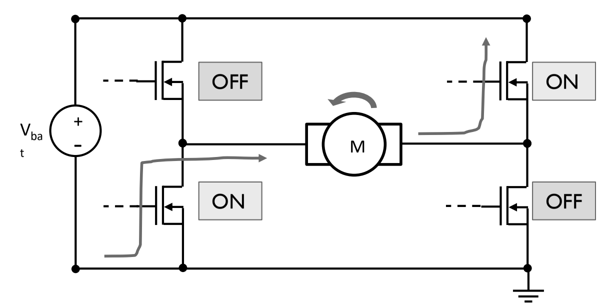

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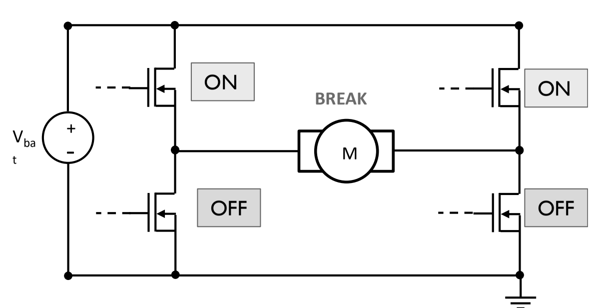

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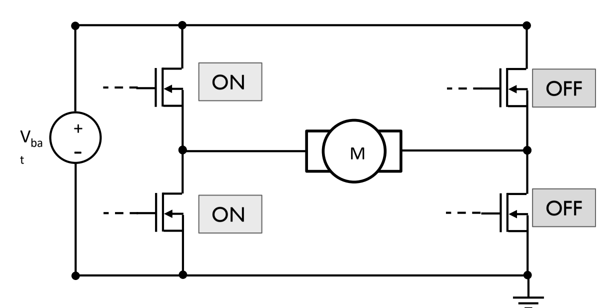
- Caution – H-bridge can short V_{dd} and ground



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- The most versatile motor controller topology
- Requires four (4) FETs per motor
- Supports:
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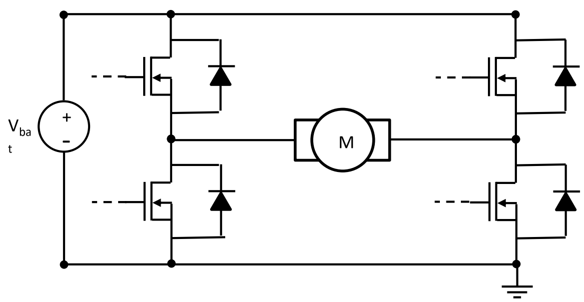
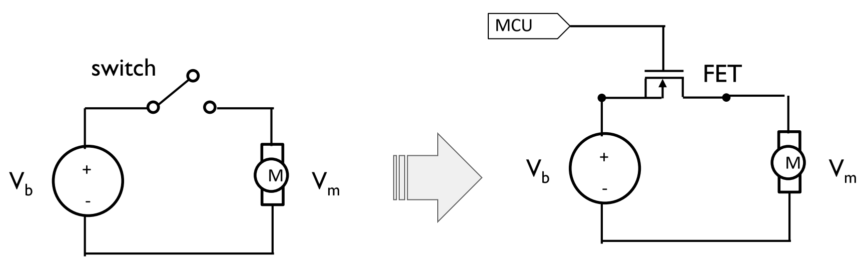
- Kick-back snubber diodes



Summary: Motor Controller Topology

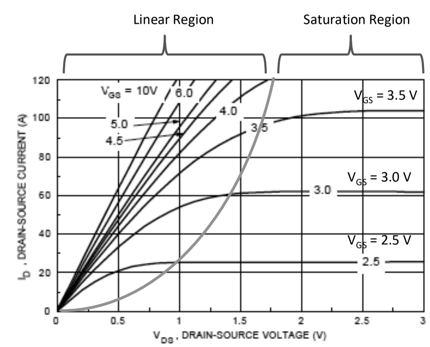
- Single FET controller allows for acceleration (ON) or coasting (OFF)
- Half-bridge allows for acceleration, breaking, and coasting
- The most versatile motor controller configuration is an H-bridge
- H-bridge allows for
  - Motor actuation both back and forth
  - Dynamic breaking
- Careful not to short battery terminals in H-bridge !

Motor Controllers



- Motor controller is an amplifier which converts the weak signals from microcontroller GPIO ports to high current that drive the motor.
- Solid-state using Power FET technology (e.g. NDP7060L)
  - Fast switching time
  - Large currents

Field Effect Transistor: A Review



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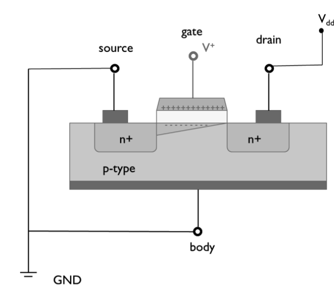

Datasheet NDP7060L

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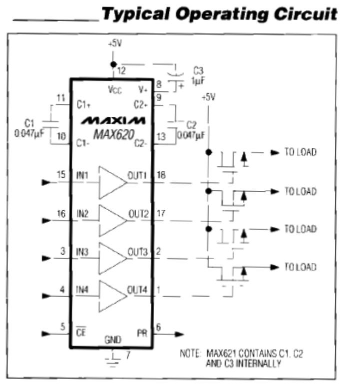

Datasheet MAX620/621

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- E.g. assume
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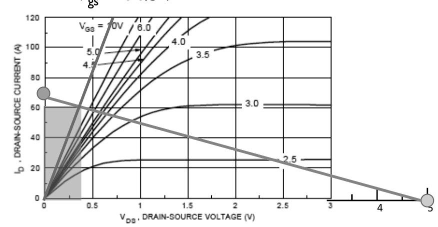
  - V_{gs} provided by the MCU

V_{gs} = 14.3 V



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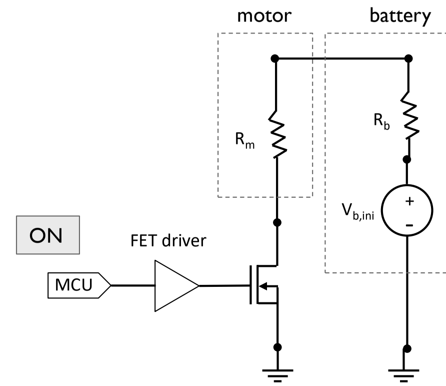

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  - Dynamic breaking
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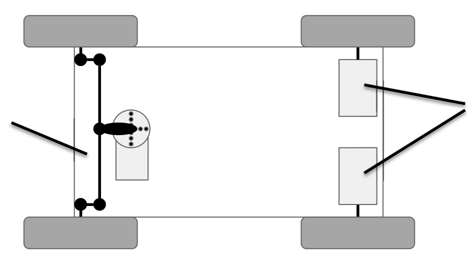
Control for Autonomous Car Actuation

- Autonomous car contains two main actuators
  - DC Motors: provide forward propulsion
  - Servos: provide steering
- Pulse-width modulation (PWM) allows for control of both

Steering Servos: PWM allows for steering control

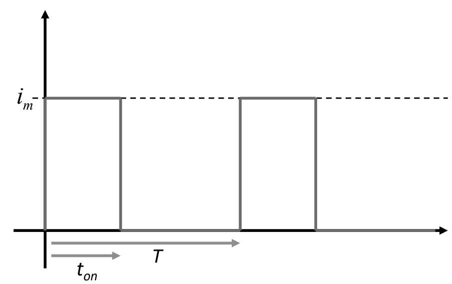


DC motors: PWM allows for velocity control

Pulse-Width Modulation (PWM): DC Motors

Pulse-Width Modulation (PWM) is used to vary torque produced by a motor while still using a driver FET only in either completely off or completely on states.

- Alternative (Bad approach):
  - Use the FET as a variable resistor
  - Large power dissipation by the FET
- Recall that: $\tau = k_t i_m$
- Pulse i_m *by switching it fast on and off*
  - *Solid-state switch*



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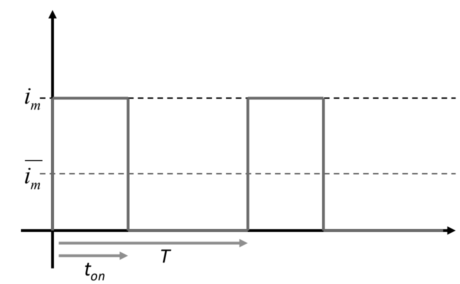
  - Use the FET as a variable resistor
  - Large power dissipation by the FET
- Recall that: $\tau = k_t i_m$
- Duty cycle: $d = \frac{t_{on}}{T}$

$\overline{i_m} = d \cdot i_m \Rightarrow \overline{\tau} = k_t \cdot \overline{i_m}$



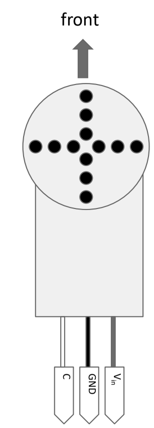
RC Servo: Introduction

- RC servos
  - Initially developed for position control in radio-controlled RC applications
  - Low precision combination of DC motor and position feedback.
  - Currently used for other than RC applications in robotics, mechatronics

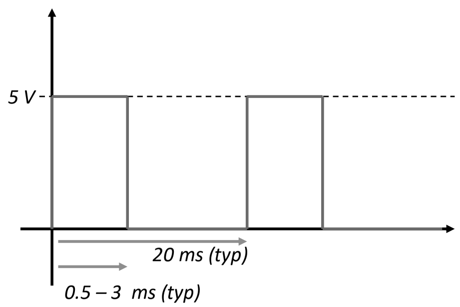
https://www.hackmeister.dk/2010/07/controlling-an-rc-servo-with-an-fpga/

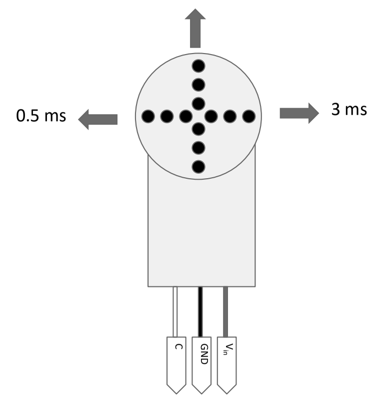
RC Servo: Control

- Servo operation:
  - Most RC servo has three wires, almost universally color coded accordingly
    - » RED – supply voltage (Vin), 5 V.
    - » BLACK – Ground (GND)
    - » WHITE – Signal (S)
- Servo can typically rotate +/- 90 deg.
- Signal (S) causes the output shaft to rotate to a set position.
  - Position encoded in a pulse train provided to S
  - Period of 20 – 30 ms (typical)
  - Pulse 0.5 – 3 ms (typical)



RC Servo: PWM





- Note: PWM in servo control different than for PWM in motors !

PWM using MCU / KL25Z128

- Usually MCUs have ability to configure PWM for use with the GPIOs
  - Using timers to provide output PWM signal to both motors and servo
  - Independent channels per timer
    - Must be configured to assign timer and channel to a desired GPIO for output
  - Configure the PWM from a timer component in Processor Expert
    - Drag down – configure to output to a certain pin
    - Be careful of timer usage
      - Can combine
    - Use methods to adjust for:
      - Duty-cycle (motor)
      - Pulse (servo)

Summary: PWM Motor and Servo Control

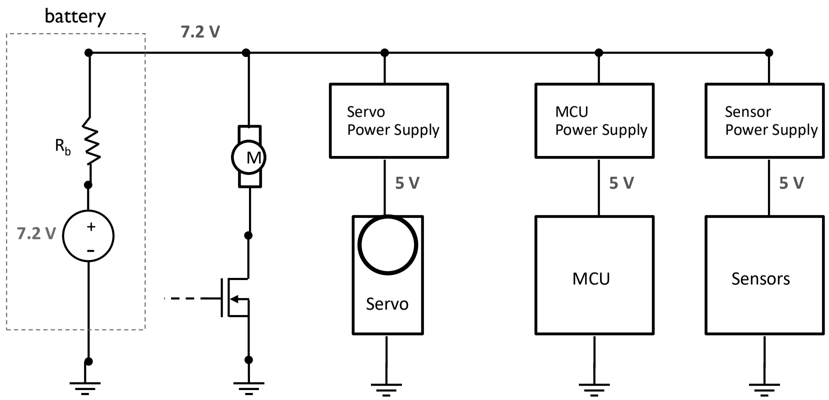
- Pulse-width modulation (PWM) is an efficient way of controlling power, and thus torque, of the motors
  - Can be used for velocity control
  - Avoids power drop over the FETs
  - **PWM duty-cycle** control the power
- Servos use an input pulse-train to control the direction of the output shaft
  - Can use PWM for control the direction of the servo
  - **PWM pulse duration** controls the direction
  - Must be calibrated

Review: Power Supply for Autonomous Car

- Different power needs for various sub-systems
- On-board power supply needed to:
  - Drive the motors (large currents)
  - Drive the servo (moderate currents)
  - Power the MCU (low currents, voltage stability)
  - Power the sensors (low currents, voltage stability
- Battery is the main reservoir of on-board power
- Many battery types
  - Most common types for electric vehicles are Lithium ion batteries (high energy density, moderate cost, large discharge/charge cycle life)

http://www.wirelessmadness.com/

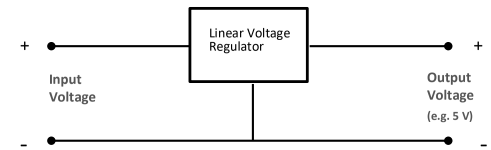
Review: Power Supply for Autonomous Car



Schematic of the required power supply for the sub-systems

Power Supply 1: Linear Voltage Regulator

- Reduces the supply voltage to a stable value set value
  - Output voltage less than input voltage
  - A variable (controlled) resistor
- Key parameters
  - Output voltage (e.g. 5 V)
  - Input voltage range
    - Output current
    - Dropout
- E.g.: LM2940CT-5.0/NOPB
  - 5 Vout
  - 0V to 26V input
  - 1 A max output
  - 500mV Dropout



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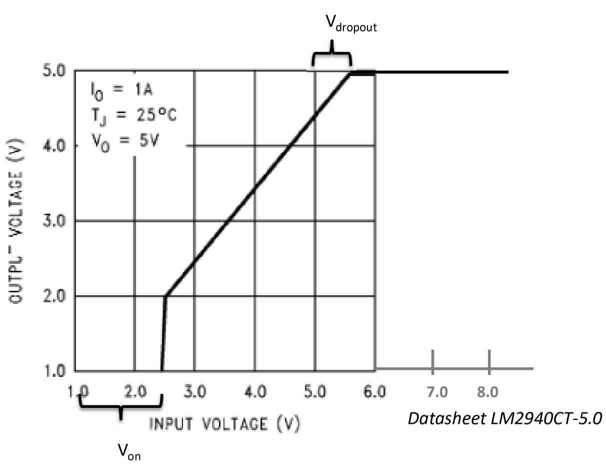
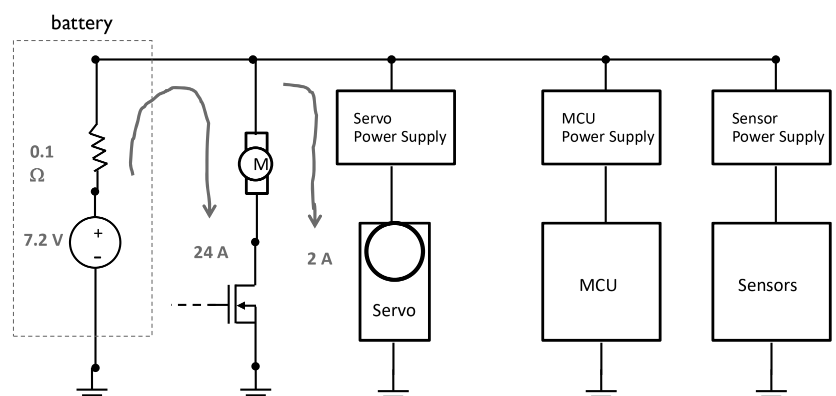


Datasheet LM2940CT-5.0

Review: Power Supply for Autonomous Car



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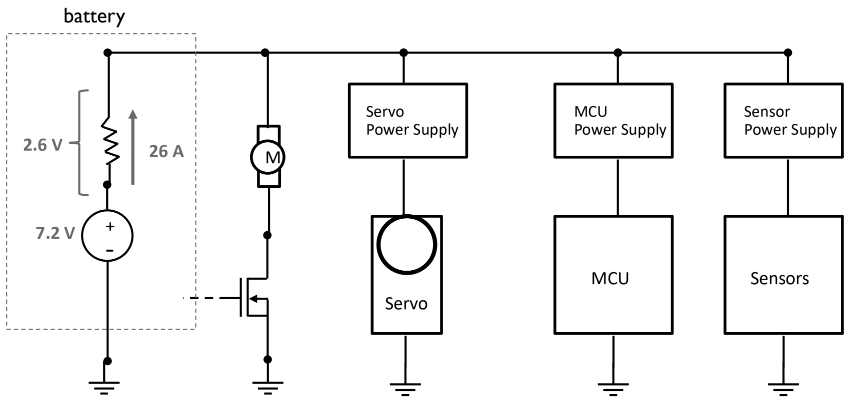


Schematic of the required power supply for the sub-systems

Power Supply II: DC/DC Converter

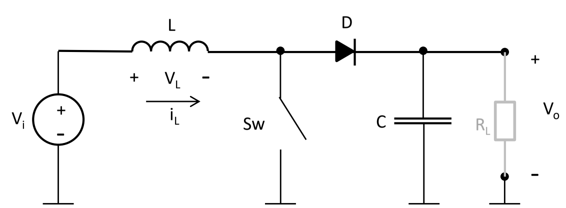
- Must elevate the voltage to provide a stable power supply (say 5 V)
- This can be down using switching power supplies

- Switching power supply:
  - Uses capacitors or inductors to store energy
  - Switches between a charge and discharge cycle
  - During the discharge cycle the energy is added or subtracted from the input voltage
  - Boost converter adds the stored voltage to boost supply voltage
  - Buck converters subtract the stored voltage to decrease the supply voltage

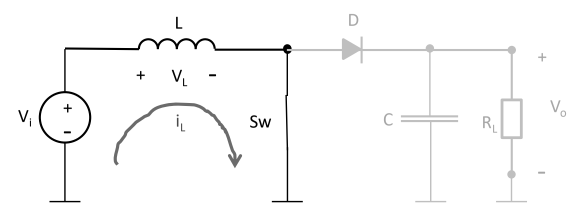
- This class will design a boost converter

Power Supply II: Boost Converter

- Used to boost the input voltage
- Uses a storage inductor as the storage element for the boost stage



Power Supply II: Boost Converter – 1 Charge Stage

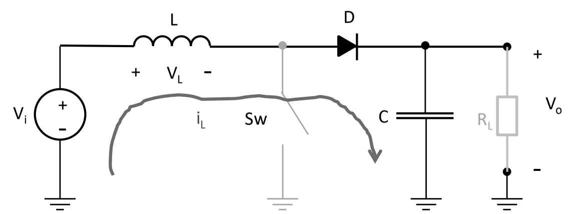


- The switch is closed
- The inductor starts storing magnetic energy by conserving current passing through

Voltage across an inductor: $V_i = L\frac{di_L}{dt}$

$$\frac{V_i}{L} = \frac{di_L}{dt}$$

Power Supply II: Boost Converter – 2 Step-up Stage



- The switch opens
- Inductor “attempts” to maintain current and thus throws large inversed voltage to maintain current i_L.
- The current i_L passes through diode D and charges up capacitor C

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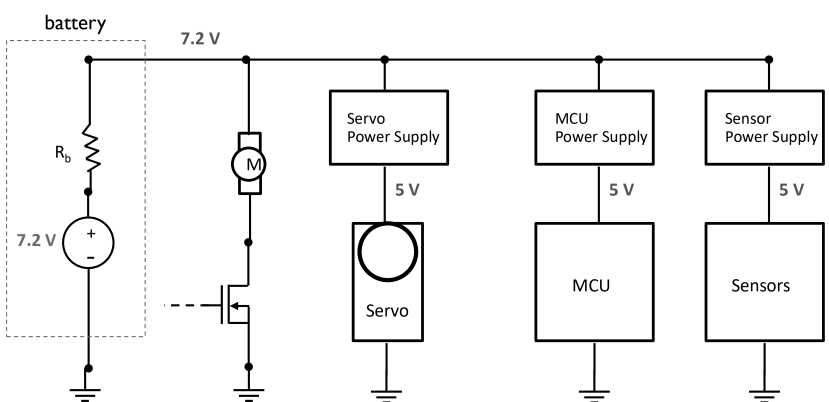

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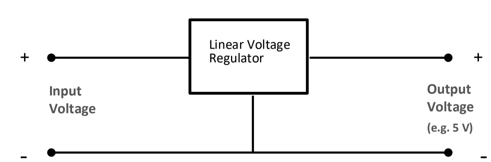
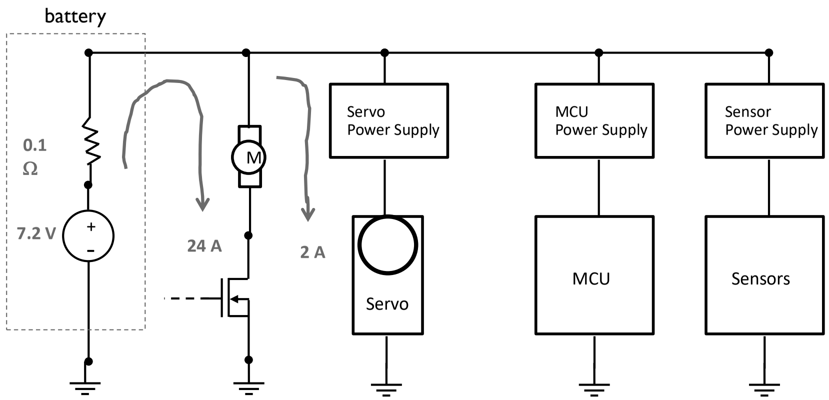
  – 1 A max output
  – 500mV Dropout

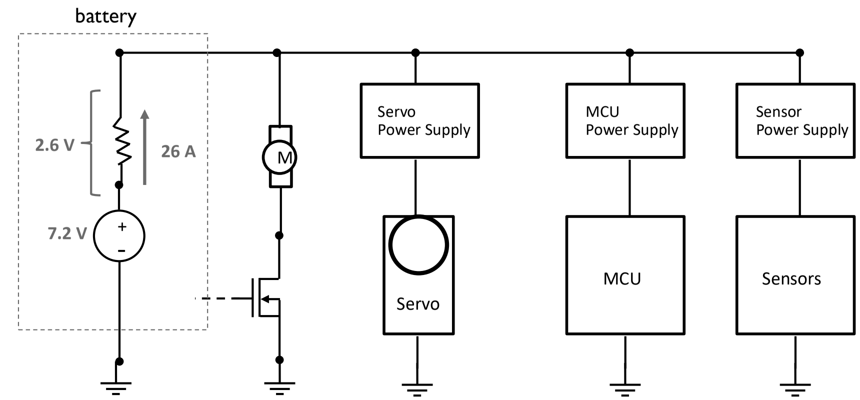


Review: Power Supply for Autonomous Car



Schematic of the required power supply for the sub-systems

Review: Power Supply for Autonomous Car



Schematic of the required power supply for the sub-systems

V_{on}

Power Supply II: DC/DC Converter

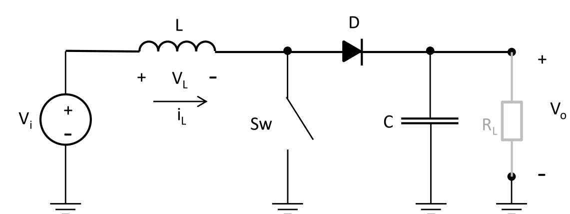
- Must elevate the voltage to provide a stable power supply (say 5 V)
- This can be down using switching power supplies

- Switching power supply:
  - Uses capacitors or inductors to store energy
  - Switches between a charge and discharge cycle
  - During the discharge cycle the energy is added or subtracted from the input voltage
  - Boost converter adds the stored voltage to boost supply voltage
  - Buck converters subtract the stored voltage to decrease the supply voltage

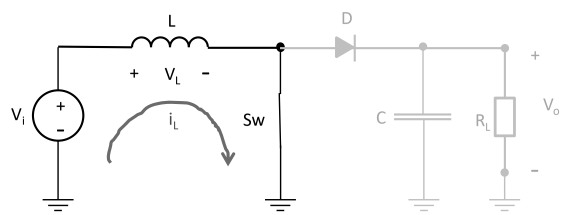
- This class will design a boost converter

Power Supply II: Boost Converter

- Used to boost the input voltage
- Uses a storage inductor as the storage element for the boost stage



Power Supply II: Boost Converter – 1 Charge Stage

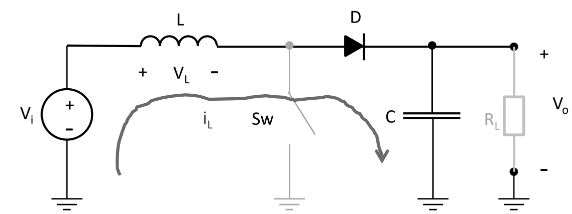


Voltage across an inductor: $V_i = L\frac{di_L}{dt}$

$$\frac{V_i}{L} = \frac{di_L}{dt}$$

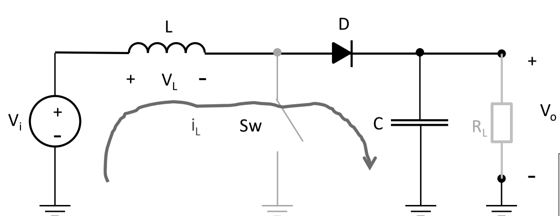
- The switch is closed
- The inductor starts storing magnetic energy by conserving current passing through

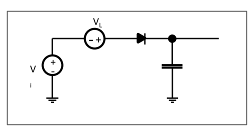
Power Supply II: Boost Converter – 2 Step-up Stage



- The switch opens
- Inductor "attempts" to maintain current and thus throws large inversed voltage to maintain current i_L.
- The current i_L passes through diode D and charges up capacitor C

Power Supply II: Boost Converter – 2 Step-up Stage





- The switch opens
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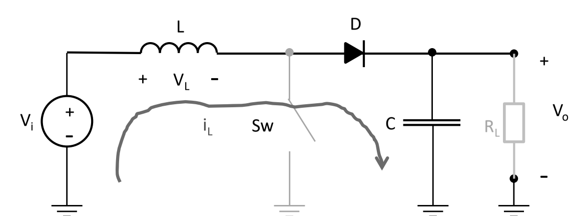
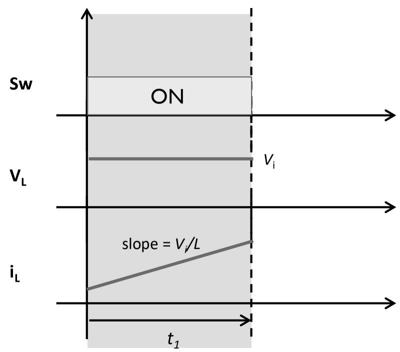
Power Supply II: Boost Converter – 2 Step-up Stage



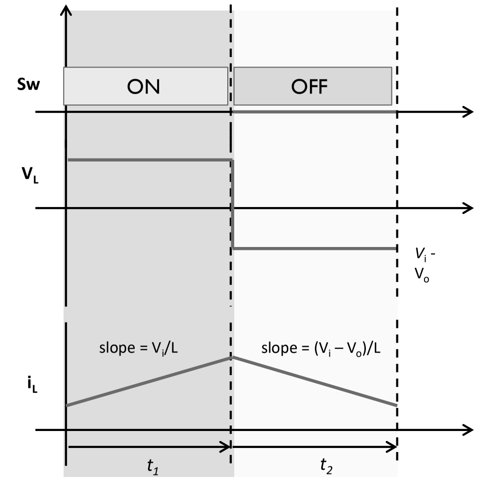
- The step-up current (slope) through the inductor is now: $\frac{V_i - V_O}{L} = \frac{di_L}{dt}$
- Inductor is discharging

Power Supply II: Boost Converter – Charge Step Revisited



The inductor is charging up. After t_1 we open the switch (Sw → OFF).

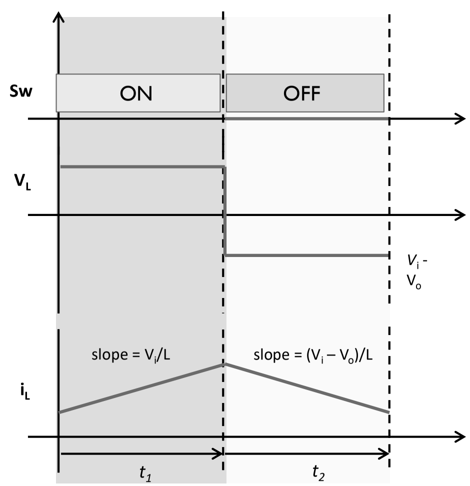
Power Supply II: Boost Converter – Step-Up Step Revisited



The inductor is charging up. After t_1 we open the switch (Sw → OFF).

The inductor is now dis-charging and transferring the charge to capacitor C for the duration of t_2.

Power Supply II: Boost Converter – Step-Up Step Revisited



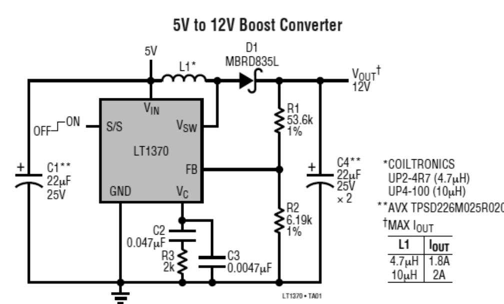
The inductor is charging up. After t_1 we open the switch (Sw → OFF).

The inductor is now dis-charging and transferring charge to capacitor C for the duration of t_2.

At steady state: $$V_o = \frac{V_i}{\left(t_2 / (t_2 + t_1)\right)}$$

Power Supply II: Boost Converter – LT1370

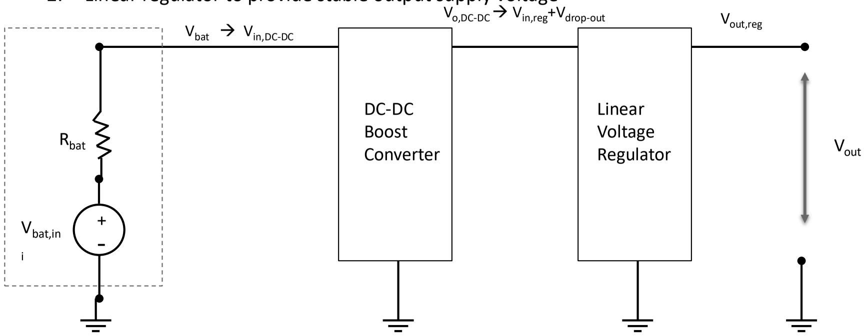
- Solid state solution switching regula
- Low (minimum) supply voltage 2.7 V
- Maximum 6A output current
- Typical application:
  - 12 V boost converter
- Use low ESR capacitors



Datasheet, LT1370, Linear Technology

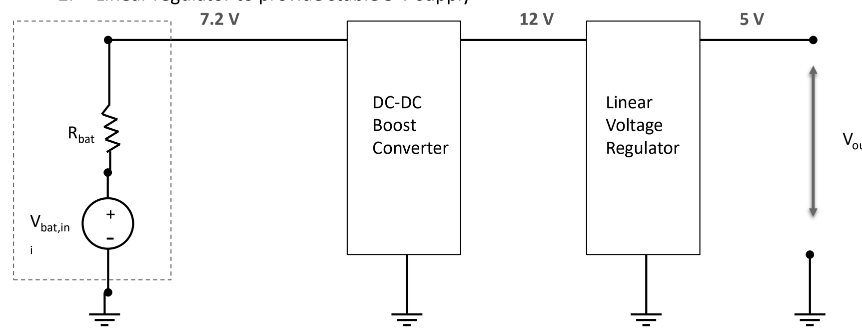
Power Supply for Autonomous Car – Entire System

- Two-component stable power-supply:
  1. Boost converter to make sure input voltage to linear regulator is always > 5 V + $V_{dropout}$
     - E.g. 12 V
  2. Linear regulator to provide stable output supply voltage



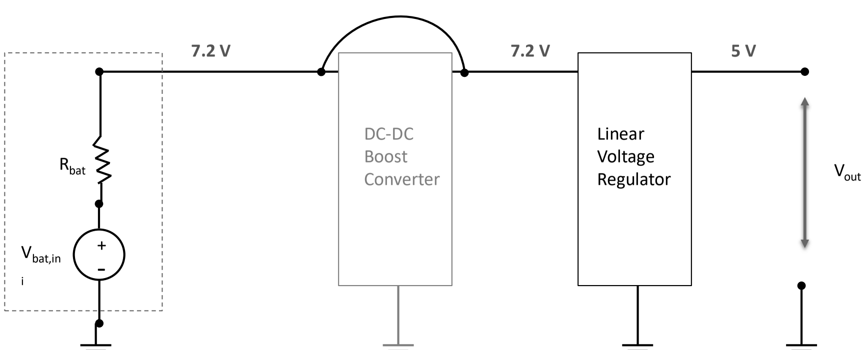
Power Supply for Autonomous Car – Entire System

- Two-component stable power-supply:
  1. Boost converter to make sure input voltage to linear regulator is always > 5 V + $V_{dropout}$
     - E.g. 12 V
  2. Linear regulator to provide stable 5 V supply



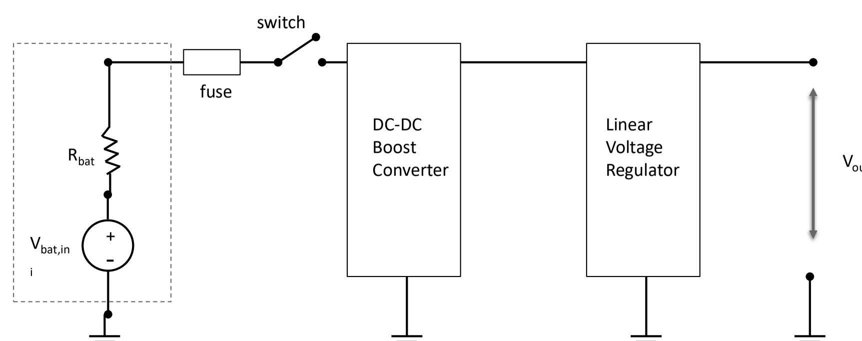
Power Supply for Autonomous Car – Entire System

- Redundancy:
  – Reliability through redundancy – can disconnect the DC-DC converter and still most likely be ok.
  – Can avoid high current conditions in SW



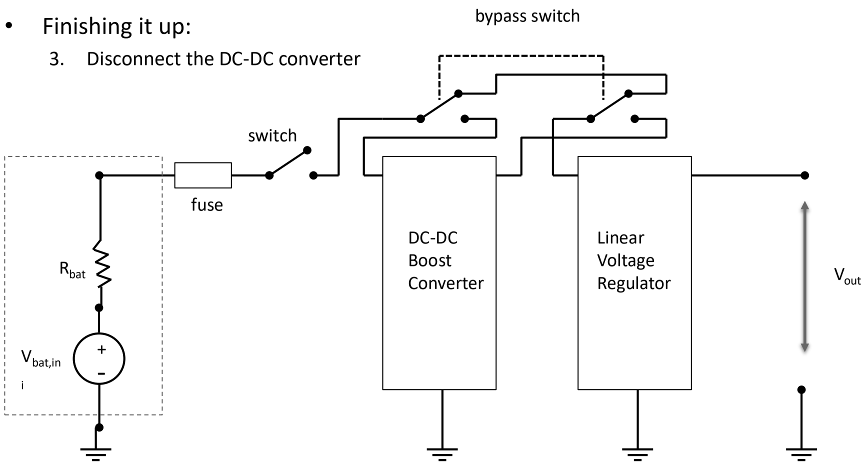
Power Supply for Autonomous Car – Entire System

- Finishing it up:
  1. Fuse (battery protection)
  2. Emergency stop switch



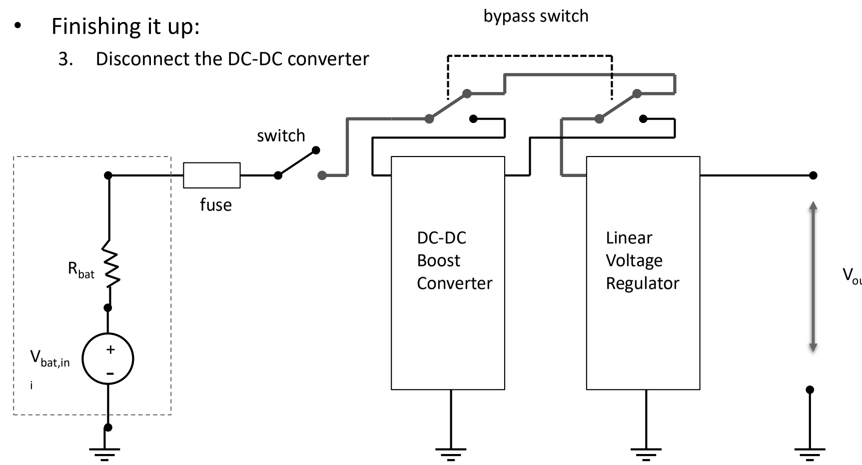
Power Supply for Autonomous Car – Entire System

- Finishing it up:
  3. Disconnect the DC-DC converter



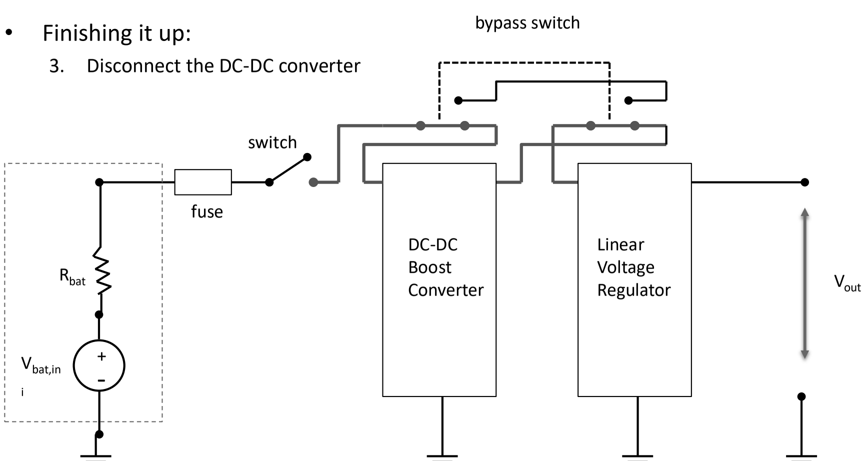
Power Supply for Autonomous Car – Entire System

- Finishing it up:
  3. Disconnect the DC-DC converter

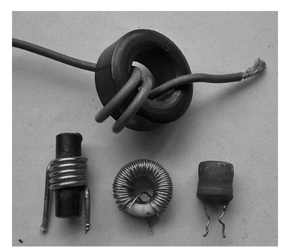


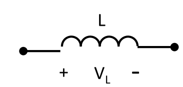
Power Supply for Autonomous Car – Entire System

- Finishing it up:
  3. Disconnect the DC-DC converter



Inductor - Review

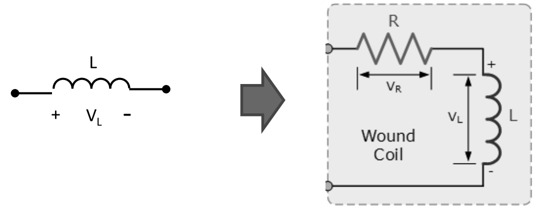




- Stores magnetic energy
- Resist changes in current
- Henry (H) in SI units (weber/ampere)
- Not purely inductive (L), but also contains resistive component (R)

Inductor - Review

$$V_L = L\frac{di_L}{dt}$$

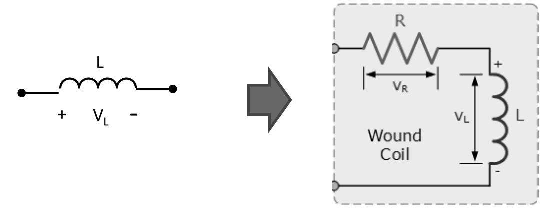


- Not purely inductive (L), but also contains resistive component (R)

$$V_L = IR + L\frac{di_L}{dt}$$

Inductor - Review

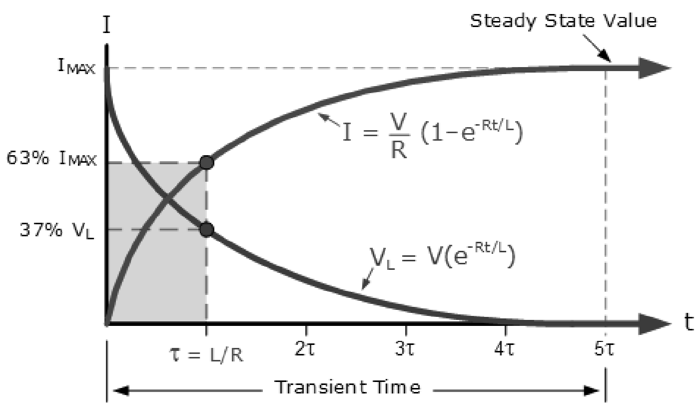
$$V_L = L\frac{di_L}{dt}$$



$$I_{(t)} = \frac{V}{R}\left(1 - e^{-Rt/L}\right) \text{ (A)}$$

$\boxed{\text{tau = L/R}}$

Inductor - Review



$$I_{(t)} = \frac{V}{R}\left(1 - e^{-Rt/L}\right) \text{ (A)}$$

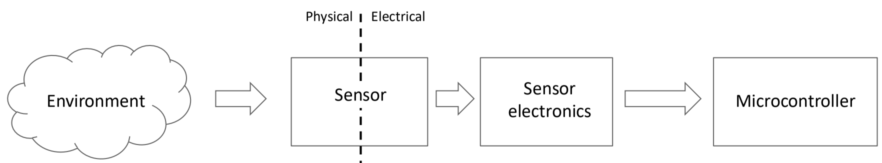
$\boxed{\text{tau = L/R}}$

Summary: Power Supply for Autonomous Car

- Reliable supply necessary to provide different voltage or current to car sub-systems
- Output battery voltage can vary as a function of current
  - Can cause problems at stall, turning
- Linear Voltage Regulator can provide a stable output voltage
  - As long and $V_{out} > V_{in} + V_{dropout}$
- A switching (DC-DC) converter can both reduce or increase the voltage a desired level
- A DC-DC boost converter, together with one or more linear voltage regulator, can provide a stable supply voltage

Sensors - An Introduction

- Obtains the information about the environment
- Provides transduction between the physical (mechanical) and electrical domains
  - Transduction: Conversion of energy between energy domains

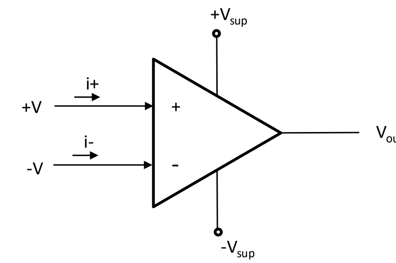


Review – Operational Amplifiers

- Operational Amplifiers (OpAmps) are commonly used to amplify (precondition) sensing signal for input to a microcontrollers
- OpAmps are analyzed as ***ideal***

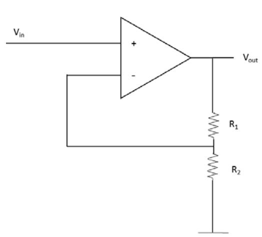
Ideal OP-Amp: $\boxed{V_{out} = A(V^+ - V^-)}$

- High input impedance (i+ ≈ 0, i- ≈ 0)
- Low output impedance
- Infinite gain (A is very large)

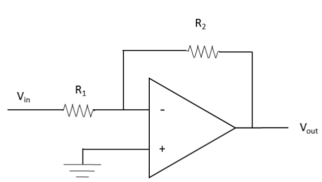


Review – Operational Amplifiers

- Two main configurations:



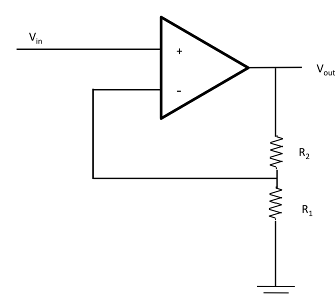
Non-inverting Amplifier



Inverting Amplifier

Review – Operational Amplifiers

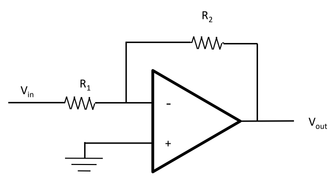
- Non-Inverting OpAmp



$$\boxed{V_{out} = \frac{R_1 + R_2}{R_1} V_{in}}$$

Review – Operational Amplifiers

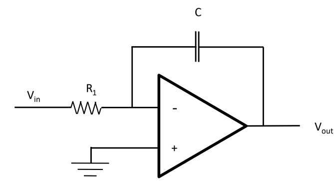
- Inverting OpAmp



$$V_{out} = -\frac{R_2}{R_1} V_{in}$$

Review – Operational Amplifiers

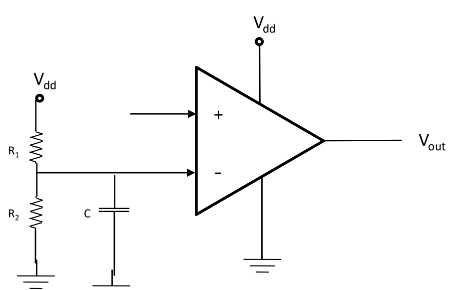
- Inverting OpAmp as charge integrator

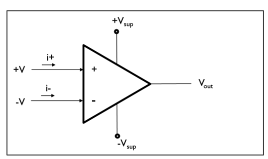


$$V_{out}(t') = -\int_0^{t'} \frac{V_{in}(t)}{RC} dt + V_{out}(0)$$

Review – Operational Amplifiers

- Single supply inverting OpAmp
  - Need to create a virtual ground at ½ Vdd





Summary: Sensors and Operational Amplifiers

- Sensors provide information about the state of the Environment to the microcontroler
- Operational Amplifiers (OpAmps) are often used to amplify the sensing signal
- OpAmps come in two flavors
  - Non-inverting
  - Inverting
- Gain of a non-inverting amplifier is always > 1
- A virtual ground can be used if an amplifier is used as single supply

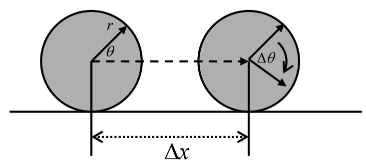
Optical Rotary Encoders and Velocity Sensing

- Velocity sensing is necessary for a car to reach a set velocity
  - Recall $\tau \propto i_m$
  - To reach the desired velocity, the car has to accelerate, i.e. increase i_m
  - Once desired velocity is reach the car has to coast, reducing i_m to counteract friction and drag
  - I_m must be larger to maintain same velocity if traversing an incline
- Velocity = distance / time
- Assuming a no-slip condition:

$$\Delta x = \Delta\theta \cdot r$$

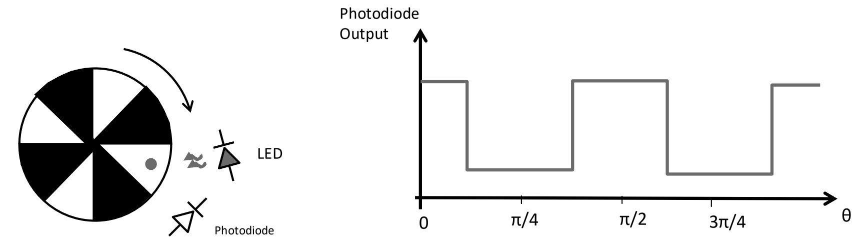
- Resulting velocity:

$$v = \frac{\Delta x}{\Delta t} = \frac{\Delta\theta}{\Delta t} \cdot r = \omega \cdot r$$

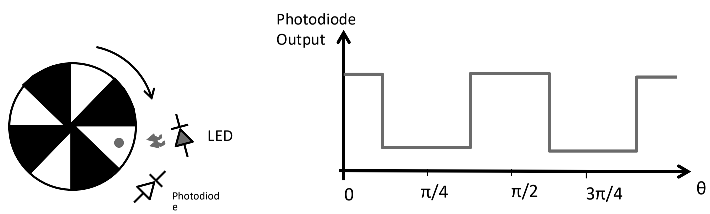


Optical Rotary Encoders and Velocity Sensing

- Optical Rotary Encoders:
  - Non-contact way to measure rotation/angular velocity
  - Can be purchased enclosed, or can be build onto the car wheel base
- Basics of operations:



Optical Rotary Encoders and Velocity Sensing



- Two ways to measure velocity:
  1. Count number of transitions (edges) within a fixed amount of time.
  2. Measure time between two transitions, i.e. the width of pulse or valley.
- Depends on the number of transitions v.s. sampling rate

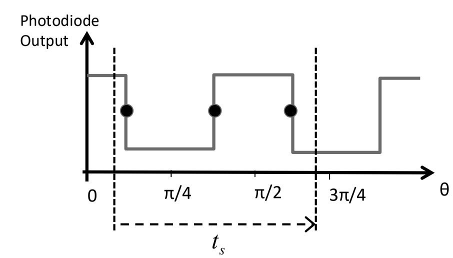
Optical Rotary Encoders and Velocity Sensing

- Count number of edges in a fixed amount of time:

$$\boxed{v = \frac{n\Delta\theta_{e-e}}{t_s} \cdot r}$$

where t_s is sampling time, n is the number of transitions, and θ_{e-e} is the angle between transitions, in this case π/4.

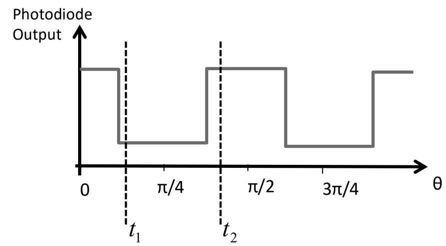
Error: $\pm \frac{\Delta\theta_{e-e}}{t_s} \cdot r$



Optical Rotary Encoders and Velocity Sensing

- Measure time between transitions:

$$\boxed{v = \frac{\Delta\theta_{e-e}}{t_2 - t_1} \cdot r}$$



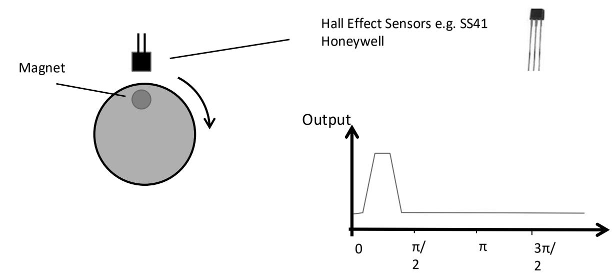
where t_1 is the time of first transition, t_2 is the time of second transition θ_{e-e} is the angle between transitions, in this case π/4.

Error: $\pm \frac{\Delta\theta_{e-e}}{t_e} \cdot r$

where t_e is the sampling interval.

Velocity Sensing – Alternative Approaches

- Optical encoder is just one way to measure velocity
- Other approaches include:
  - Back EMF from the motors
  - Other types of proximity sensors to mark a revolution of the wheel
    - Good example is Hall-effect sensors

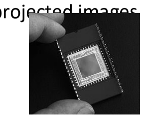


Summary: Optical Rotary Encoders and Velocity Sensing

- Non-contact way of measuring rotation, can be integrated on the wheel
- Assuming no-slip conditions, wheel rotation corresponds to distance traveled
- An optical rotary encoder wheel can be used to measure rotation
- Two approaches:
  - Measure time between transitions
  - Count number of transitions within a time interval
  - Which approach to chose depends on: velocity, sampling time, allowable error
- Other approaches, such as sensing back EMF or hall effect (magnetic) sensing can be used to estimate the velocity

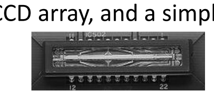
Optical Line Camera and Line Following

- A vision system is a key component in any autonomously driving car
- Optical camera projects an image onto a surface composed of light sensitive pixels
- Charge Coupled Device (CCD) image sensor:
  - An array of light sensitive pixels fabricated on a silicon chip, used to detect projected images
  - 2D array an essential component in many digital cameras
- Sophisticated image reconstruction algorithms usually need



wikipedia

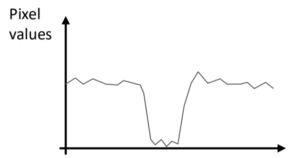
- Line or edge following can be constructed using a 1D CCD array, and a simplified algorithm.

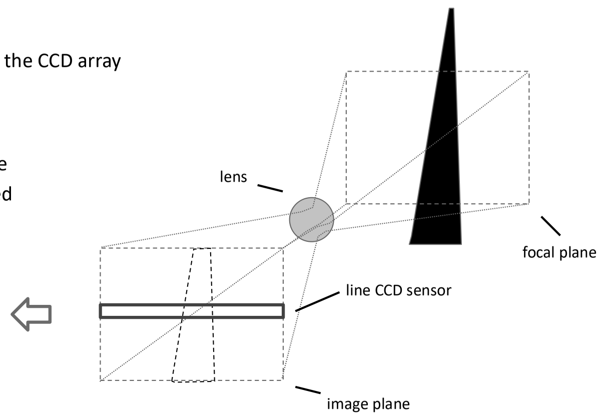


wikipedia

Optical Line Camera and Line Following

- Line camera contains
  - 1D CCD array (line)
  - Lens to focus the image across the CCD array
- Within the image plane
  - Image still projected on a plane
  - Only one line of image detected

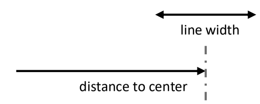


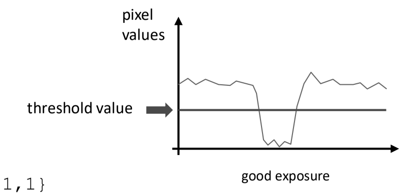


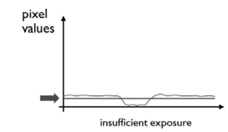
Optical Line Camera and Line Following

- Detecting line center
  - Thresholding an effective method
  - NOTE: need to adjust the level of thresholding as well as the exposure level
- Pixels (image elements) as array of 1's and 0's
- Simple algorithms to detect line locations
  - Pixel counting

{1,1,1,1,1,1,0,0,0,0,0,1,1,1,1,1,1}

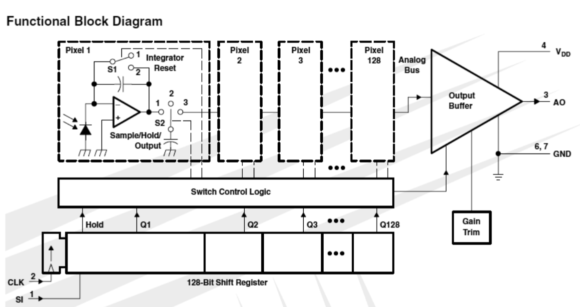


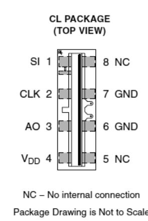




Optical Line Camera and Line Following

- Recommended line camera: TAOS TSL1401CL
  - 128 x 1 linear optical sensor array
  - 3 – 5 V V_{dd} power supply

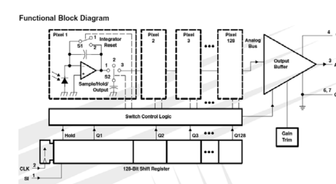




Optical Line Camera and Line Following

- Sensor functionality:

$$AO = V_{out} = V_{drk} + R_e \cdot E_e \cdot t_{\text{int}}$$



- The pixels are serially read
- SI marks the start of the readout sequence
- Each clock pulse marks the transition to a new pixel, accessible through AO
- During reading, pixels are in parallel exposed
- Exposure time (integration time):

$$t_{\text{int}} = (129 - 18) \cdot t_{CLK} + t_{qt}$$

Optical Line Camera and Line Following

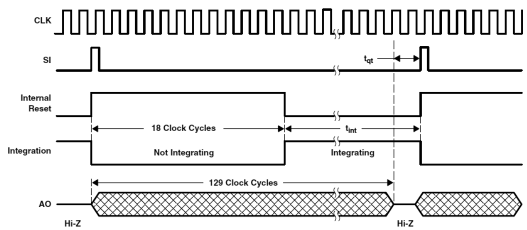
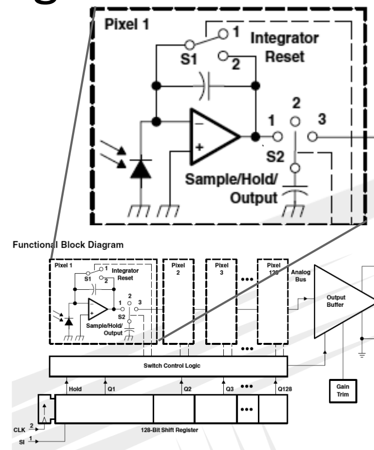


Figure 1. Timing Waveforms



Optical Line Camera and Line Following

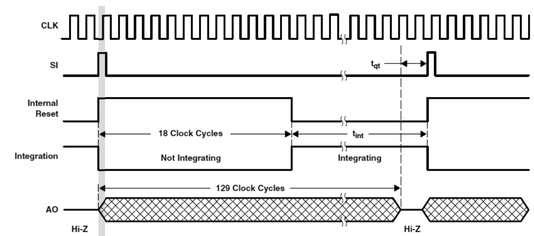
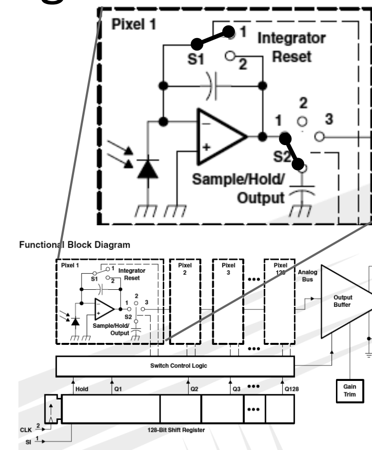


Figure 1. Timing Waveforms



Optical Line Camera and Line Following

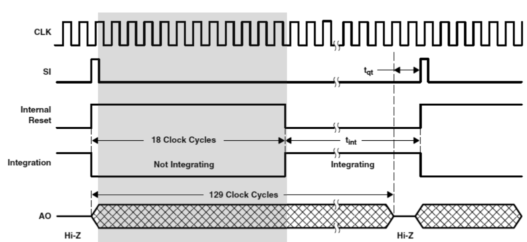
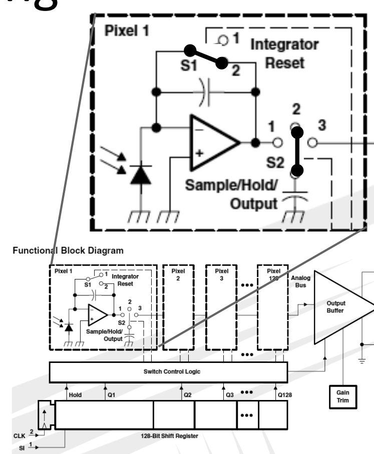


Figure 1. Timing Waveforms



Optical Line Camera and Line Following

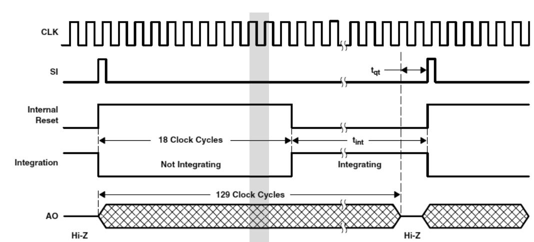
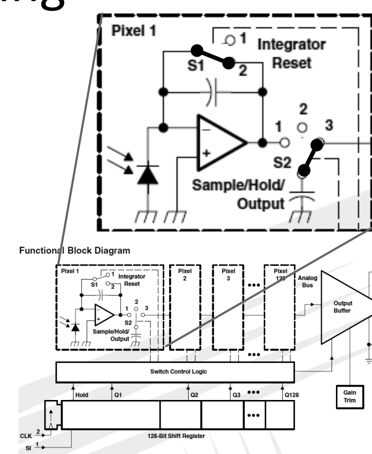


Figure 1. Timing Waveforms



Optical Line Camera and Line Following

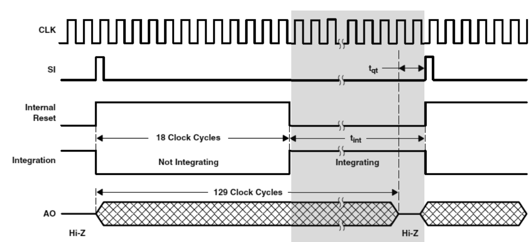
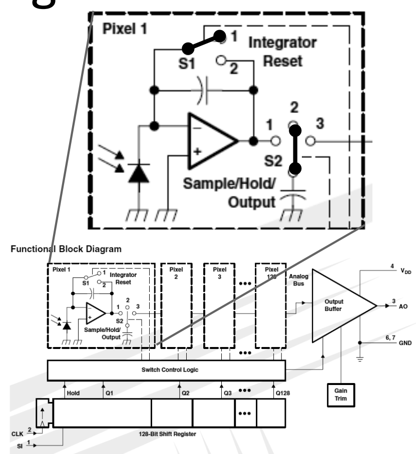


Figure 1. Timing Waveforms

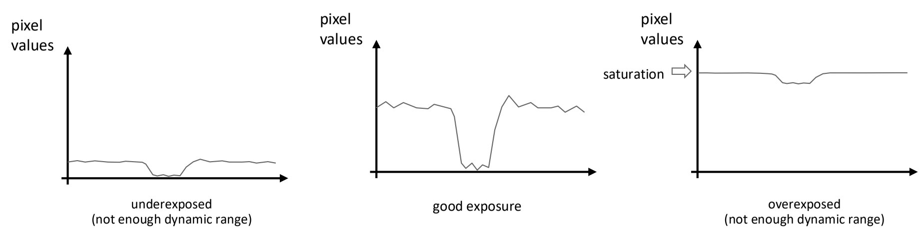


Exposure Adjustment

- Recap sensor functionality: $$AO = V_{out} = V_{drk} + R_e \cdot E_e \cdot t_{\text{int}}$$ $$t_{\text{int}} = (129 - 18) \cdot t_{CLK} + t_{qt}$$
- Note exposure time is proportional to t_{int}
- Can adjust exposure by adjusting the integration time !
  - Lower CLK frequency (readout) in low-light conditions
  - Higher CLK frequency (readout) in high-light conditions
- Potential problem
  - Slow down control loop
  - CLK exceeds the ADC frequency
- Solution:
  - Two cycles, 1) exposure and 2) readout.
  1. Fast sequence – expose only, ignore readout on AO
  2. Slow sequence – readout only, read stored data in cycle 1)

5 KHz < f_{clock} < 8 MHz

Exposure Adjustment



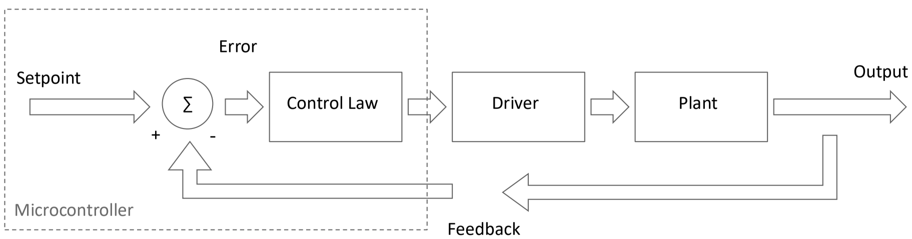
- Exposure should be adjusted to maximize dynamic range
  - Can be done online during line following
  - Can be done during the control loop

Summary: Optical Line Camera and Line Following

- A 2D light-sensitive pixel array is used in cameras for image capture
- A 1D pixel array (line) can be used for line detection – line camera
- Can be used for optical line following
  - Focus sensor on the line
  - Thresholding can be used to determine the center of the line
- Line camera provided with the kit uses TAOS TSL1401CL sensor
  - 128 pixels
  - Variable integration (exposure) time
  - Sequential (serial) output via AO, controlled through CLK and SI
- Exposure can be varied to accommodate changes in lighting conditions
  - Changing the CLK frequency
  - Can be done dynamically to account for changes in light conditions

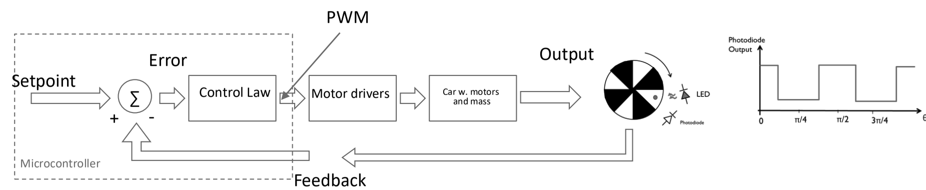
Introduction to Feedback Control

- Control System:
  - System that describes the control algorithm and the interaction with the environment
- Control System Diagram:
  - Symbolic description of the control system



Velocity Control

- Implementing velocity control:

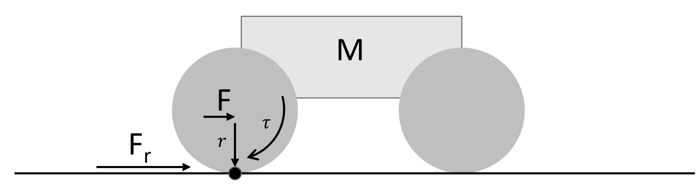


Modeling Autonomous Car

- Controlling the autonomous car requires modeling of its physics
- Simplified control problem:
  - **Velocity Control:** Consider the dynamics of motion, drag, and torque affecting the forward motion of the car, but disregard effects due to steering
  - **Steering Control:** Consider line following, subject to non-holonomic constraints associated with steering, but no dynamics (quasi-static system only)
- Nonholonomic Constrains (for Autonomous Car):
  - Constrains that prevent motion in all directions. The car cannot move sideways.
- Configuration Space (C-space):
  - Parameters used to completely define the coordinates of the autonomous car.

Modeling Autonomous Car – Velocity Control

- Controlling the autonomous car requires understanding of its physics
- Recall that velocity control handled through PWM

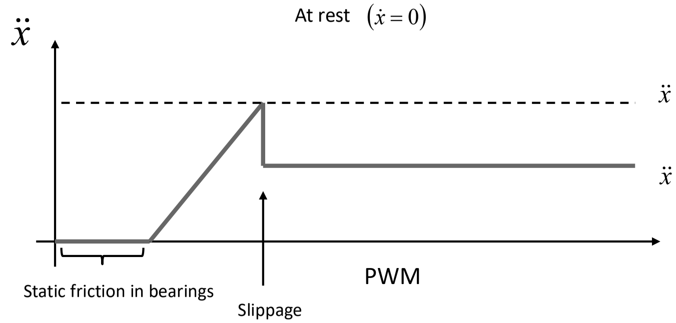


$F = ma = m\ddot{x} = \frac{\bar{\tau}}{r}$ ⇨ Requires friction (resulting in Fr)

Modeling Autonomous Car – Velocity Control - Friction

- Both dynamic and static friction are present in slip-less rolling
- Coulomb friction: $F_r = \mu N$

At rest $(\dot{x} = 0)$

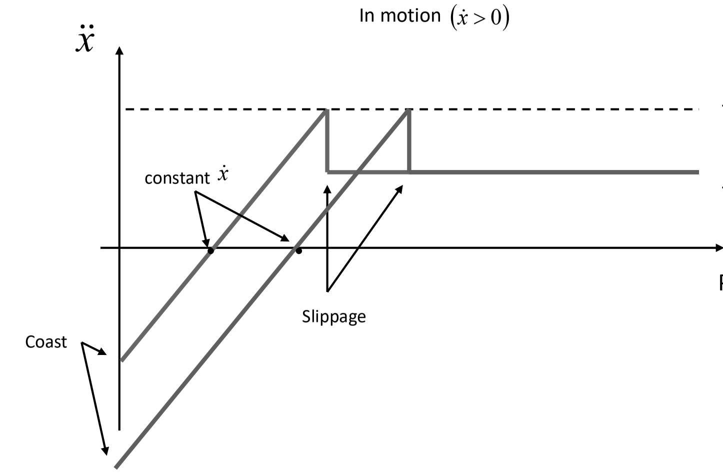


$$\ddot{x} = \frac{F_r}{m} = \frac{\mu_s N}{m}$$

$$\ddot{x} = \frac{F_r}{m} = \frac{\mu_d N}{m}$$

Modeling Autonomous Car – Velocity Control - Friction

In motion $(\dot{x} > 0)$

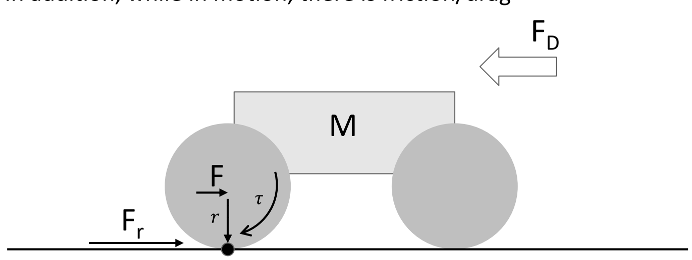


$$\ddot{x} = \frac{F_r}{m} = \frac{\mu_s N_s}{m}$$

$$\ddot{x} = \frac{F_r}{m} = \frac{\mu_d N_d}{m}$$

Modeling Autonomous Car – Velocity Control

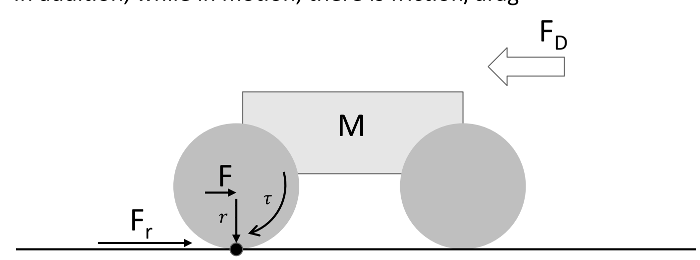
- In addition, while in motion, there is friction/drag



$$F = \frac{\bar{\tau}}{r} = m\ddot{x} + F_D = m\ddot{x} + B\dot{x}$$

Modeling Autonomous Car – Velocity Control

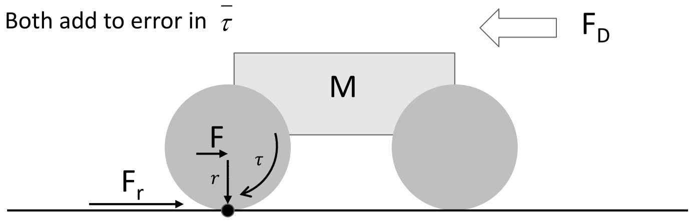
- In addition, while in motion, there is friction/drag



$$F = \frac{\bar{\tau}}{r} = m\ddot{x} + F_D = m\ddot{x} + B\dot{x}$$

Modeling Autonomous Car – Velocity Control

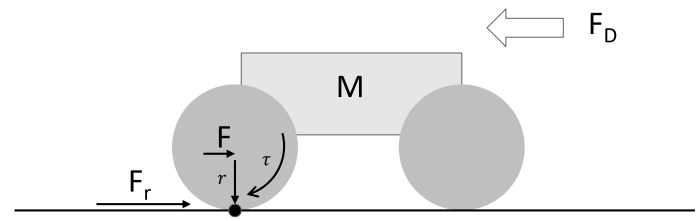
- Recall that $\bar{\tau} = k_t \cdot \overline{i_m}$ which depends on the battery voltage and back EMF !
- Both add to error in $\bar{\tau}$



$$F = \frac{\bar{\tau}}{r} = m\ddot{x} + F_D = m\ddot{x} + B\dot{x} \qquad \bar{\tau} = k_t \cdot \overline{i_m} = k_t\left(\frac{V_B - k_e\dot{\theta}}{R_m}\right)$$

Modeling Autonomous Car – Velocity Control

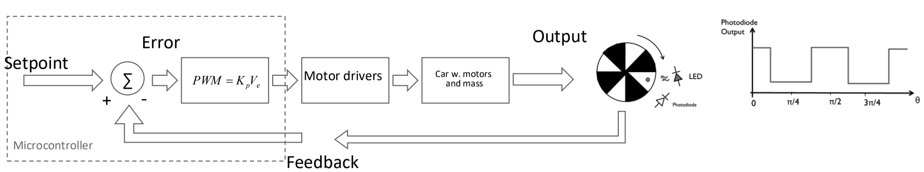
- External disturbances due to drag, friction, battery voltage, back EMF, and incline suggest closed-loop control of PWM for velocity



- Recommend closed-loop control law:
  - PWM = $K_p(V_{desired} - V_{actual})$
  - $V_{desired} > V_{actual}$, PWM is increased

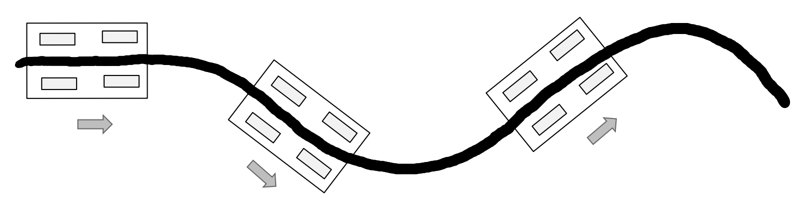
Velocity Control

- Implementing velocity control:



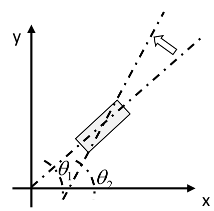
Steering Control - Introduction

- Objective for Steering Control:
  - Keep the track centered on the track
  - Track is assumed a black centerline



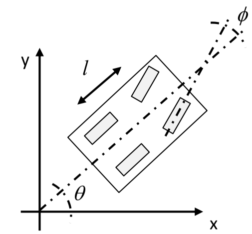
Modeling Autonomous Car – Non-Holonomic System

- An autonomous car is non-holonomic, i.e. its motion is subject to non-holonomic constrains of its motion. This means that it cannot move in all directions.
  - Only move forward and turn
- Simplified Systems: Unicycle
  - Configuration: $\vec{q} = \begin{pmatrix} x \\ y \\ \theta \end{pmatrix}$
  - Equation of motion: $\dot{q} = \begin{pmatrix} 0 \\ 0 \\ 1 \end{pmatrix} u_1 + \begin{pmatrix} \cos\theta \\ \sin\theta \\ 0 \end{pmatrix} u_2$



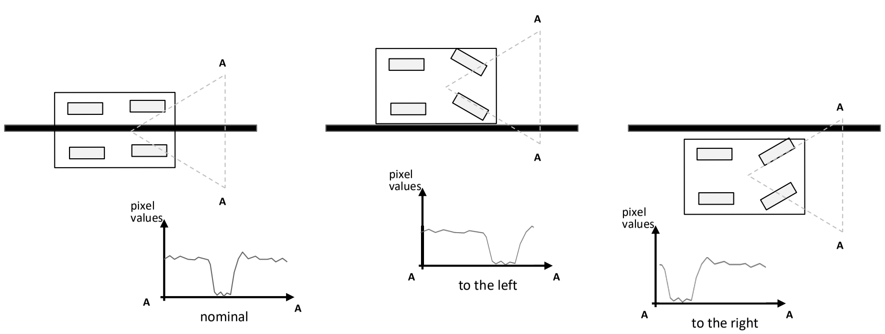
Modeling Autonomous Car – Non-Holonomic System

- An autonomous car is non-holonomic, i.e. its motion is subject to non-holonomic constrains of its motion. This means that it cannot move in all directions.
  - Only move forward and turn →rotation for steering wheel is important
- Autonomous Car
  - Configuration: $\vec{q} = \begin{pmatrix} x \\ y \\ \theta \\ \phi \end{pmatrix}$
  - Equation of motion: $\dot{q} = \begin{pmatrix} 0 \\ 0 \\ 0 \\ 1 \end{pmatrix} u_1 + \begin{pmatrix} \cos\theta \\ \sin\theta \\ \tan\phi / l \\ 0 \end{pmatrix} u_2$



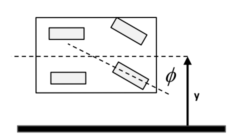
Modeling Autonomous Car – Non-Holonomic System

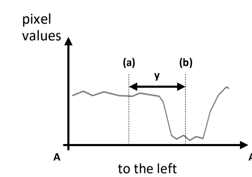
- Line (track) following
  - Keep line in the center of car
  - Disturbances will perturb the car from being over the center of the car



Modeling Autonomous Car – Non-Holonomic System

- Proportional control for steering
  - Recall - Proportional velocity control: PWM = Kp(Vdesired – Vactual)
  - y - distance between center of chassis (a) and imaginary center line (b)



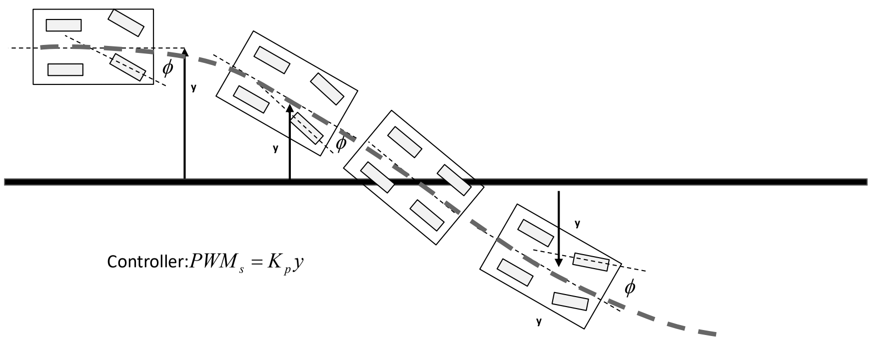


Proposed control law: $PWM = K_p y$

BAD

Line Following – Proportional Control

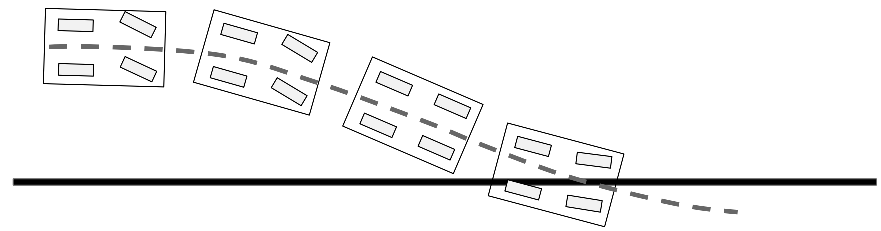
- Proportional control for steering
  - Purely proportional steering poses a problem (oscillation, overshoot)



Controller: $PWM_s = K_p y$

Line Following – Proportional/Derivative Control

- Proportional – derivative control for steering
  - Adding a derivative term can dampen the overshoot.

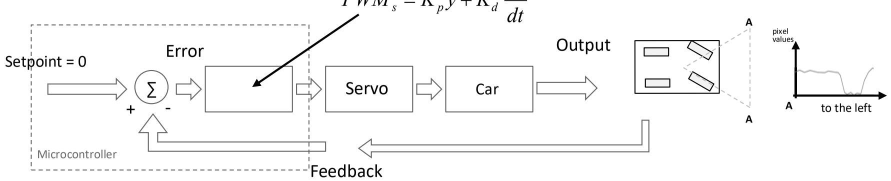


Controller: $PWM_s = K_p y + K_d \frac{dy}{dt}$

Steering Control

- Implementing steering control:

$$PWM_s = K_p y + K_d \frac{dy}{dt}$$



PID Control - Review

- Proportional Integral Derivative (PID) Controller
  - Feedback control algorithm
  - Originates from industrial control systems

$$u(t) = \underbrace{K_p e(t)}_{\text{Proportional term}} + \underbrace{K_i \int_0^t e(\tau)d\tau}_{\text{Integral term}} + \underbrace{K_d \frac{de(t)}{dt}}_{\text{Derivative term}}$$

  - **Proportional Term:** Main contributor to reducing the error. Drawback, will always have an error term.
  - **Integral Term:** Accounts for past error, for example if output is not strong enough to reduce error. Accumulating error will increase u(t)
  - **Derivative Term:** Accounts for future (trends in) error. (rate of change)