Mechatronics Systems Design Laboratory

ECE 491

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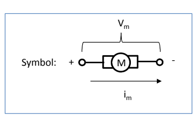
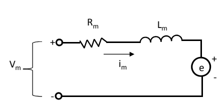
Upcoming Checkout

- This week:
  - Altium Tutorial (Lab 3)
- Next week:
  - PWM(Lab 4)
  - Quiz 1 next Tuesday (2/14/2017)

- BB up
- Project proposal due Tuesday 2/14 (project proposal guidelines on BB soon)

Motor: Electrical Equivalent Circuit





$V_{emf} = k_e \omega$

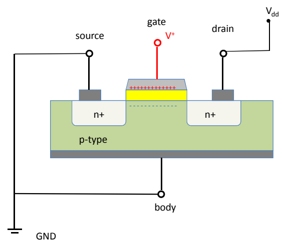
$\tau = k_t i_m$ $\quad V_m = k_e \omega + i_m R_m$ ← Assumes $\frac{di_m}{dt} \approx 0$

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

Field Effect Transistor: A Review

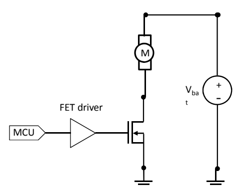
FET Operation (n-channel)

- 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



Motor Controllers Topologies

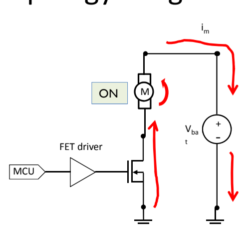
- Single FET motor controllers have the simplest topology
  - Can only accelerate, and coast to stop
- Other topologies allow for:
  - Breaking
  - Backwards motion
- Most common, full H-bridge
- Possible to use a half-bridge to simplify the controller design



single transistor controller

Motor Controllers Topology: Single FET

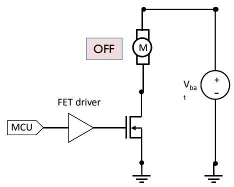
- FET ON
  - Accelerates



single transistor controller

Motor Controllers Topology: Single FET

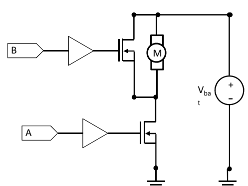
- FET OFF
  - Coasts (open connectors) to stop



single transistor controller

Motor Controllers Topology: Half-Bridge

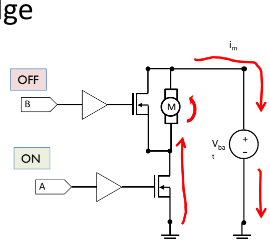
- It is possible to accelerate breaking by use the concept of **dynamic breaking**
- The V_{emf} generated by the motor is used to drive current through armature to cause breaking of the motor
- Required additional FET



Half-bridge

Motor Controllers Topology: Half-Bridge

- Accelerate:
  - A ON, B OFF



Half-bridge

Motor Controllers Topology: Half-Bridge

- Dynamic Breaking:
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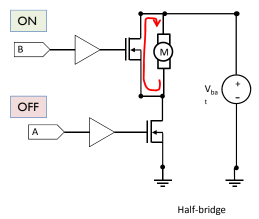
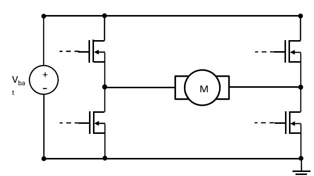


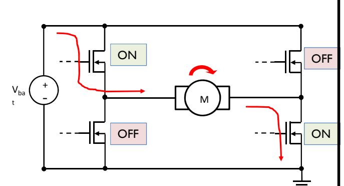
Motor Controllers Topology – H-Bridge

- 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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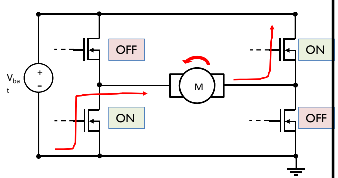

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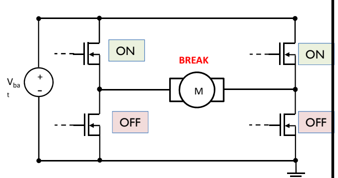

Motor Controllers Topology – H-Bridge

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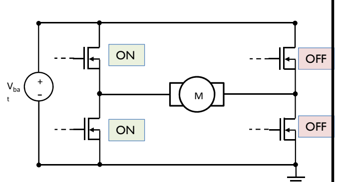
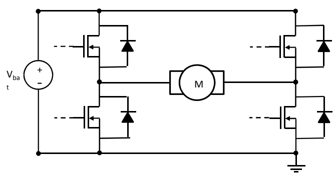
- Caution – H-bridge can short V_{dd} and ground



Motor Controllers Topology – H-Bridge

- The most versatile motor controller topology
- Requires four (4) FETs per motor
- Supports:
  - Motion forward
  - Motion backward
  - Breaking
- Caution – H-bridge can short V_{dd} and ground
- Kick-back snubber diodes

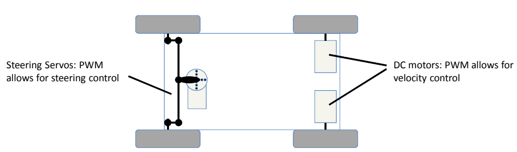


Summary: Motor Controller Topology

- 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 !

Control for Autonomous Car Actuation

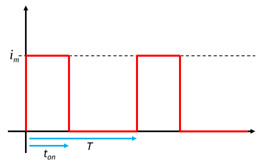
- Autonomous car contains two main actuators
  - DC Motors: provide forward propulsion
  - Servos: provide steering
- Pulse-width modulation (PWM) allows for control of both



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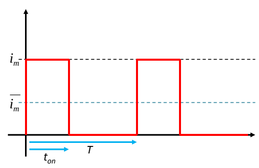
- Alternative (Bad approach):
  - Use the FET as a variable resistor
  - Large power dissipation by the FET
- Recall that: $\tau = k_t i_m$
- Duty cycle: $d = \frac{t_{on}}{T}$

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

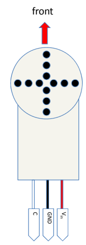


RC Servo: Introduction

- 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

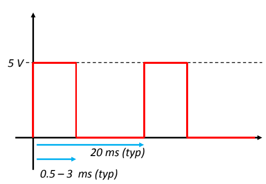
https://www.hackmeister.dk/2010/07/controlling-an-rc-servo-with-an-fpga/

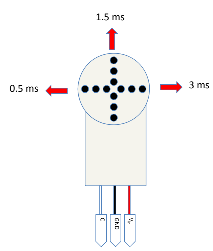
RC Servo: Control



- 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

- 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

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

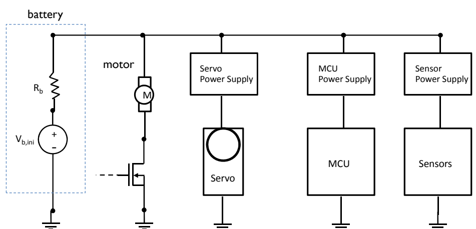
- Review of power supply for autonomous car
- Power Supply I: Linear Voltage Regulators
- Power Supply II: DC/DC converter
- Complete power supply solution

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)

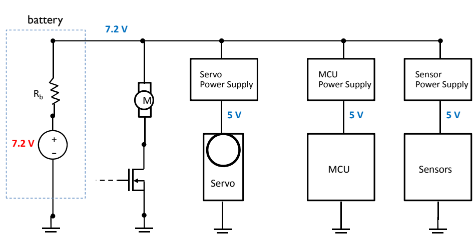
http://www.wirelessmadness.com/

Review: Power Supply for Autonomous Car



Schematic of the required power supply for the sub-systems

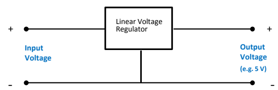
Review: Power Supply for Autonomous Car



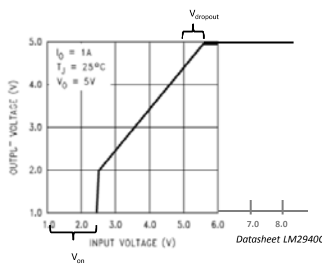
Schematic of the required power supply for the sub-systems

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

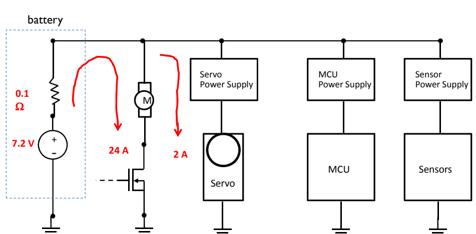


Power Supply 1: Linear Voltage Regulator



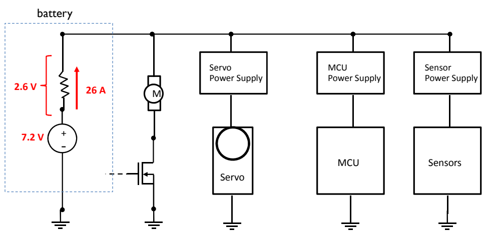
Datasheet LM2940CT-5.0

Review: Power Supply for Autonomous Car



Schematic of the required power supply for the sub-systems

Review: Power Supply for Autonomous Car



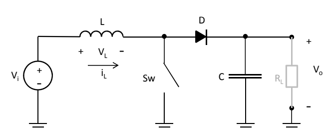
Schematic of the required power supply for the sub-systems

Power Supply II: DC/DC Converter

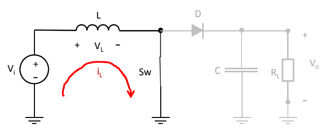
- Must elevate the voltage to provide a stable power supply (say 5 V)
- This can be down using switching power supplies
- Switching power supply:
  - Uses capacitors or inductors to store energy
  - Switches between a charge and discharge cycle
  - During the discharge cycle the energy is added or subtracted 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

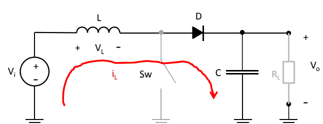


Voltage across an inductor: $V_i = L\frac{di_L}{dt}$

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

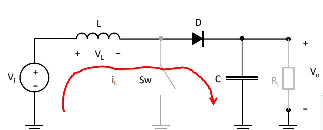
- The switch is closed
- The inductor starts storing magnetic energy by conserving current passing through

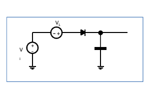
Power Supply II: Boost Converter – 2 Step-up Stage



- 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





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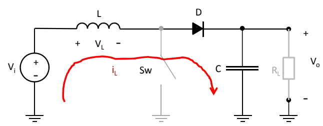
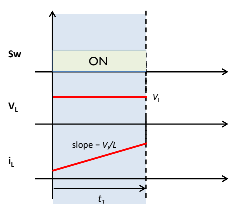


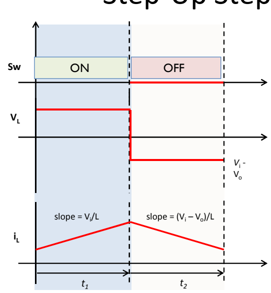
- The step-up current (slope) through the inductor is now: $\frac{V_I - V_O}{L} = \frac{di_L}{dt}$
- Inductor is discharging

Power Supply II: Boost Converter – Charge Step Revisited



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

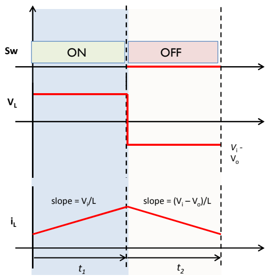
Power Supply II: Boost Converter – Step-Up Step Revisited



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

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

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



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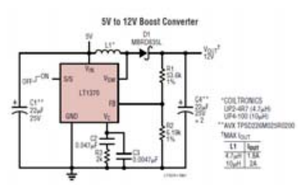
At steady state: $V_o = \dfrac{V_i}{\left(t_2 / (t_2 + t_1)\right)}$

Power Supply II: Boost Converter – LT1370

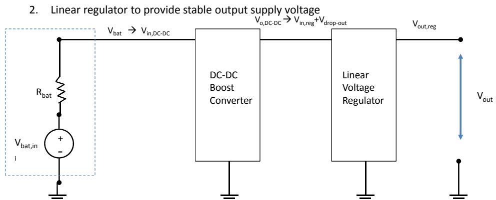
- Solid state solution switching regula
- Low (minimum) supply voltage 2.7
- Maximum 6A output current
- Typical application:
  - 12 V boost converter
- Use low ESR capacitors



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:
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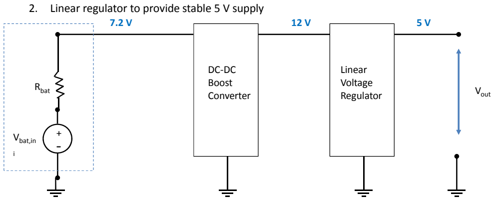
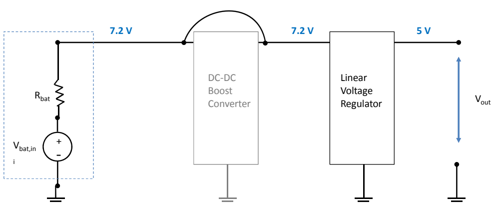
     - E.g. 12 V
  2. Linear regulator to provide stable 5 V supply



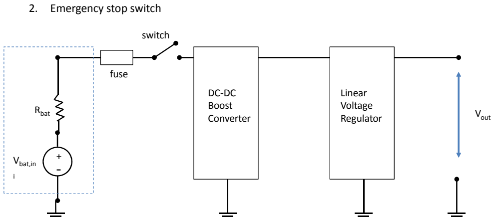
Power Supply for Autonomous Car – Entire System

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



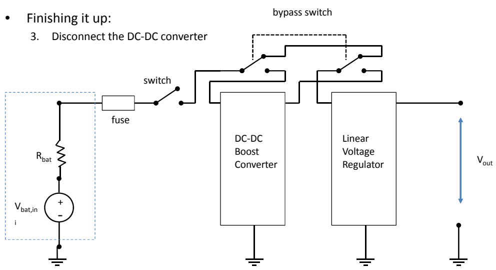
Power Supply for Autonomous Car – Entire System

- 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

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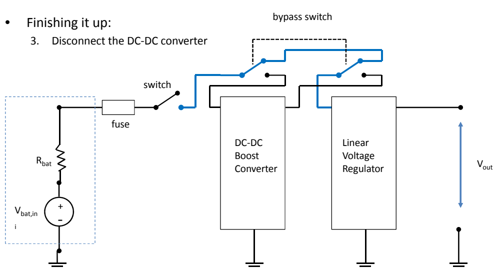

Power Supply for Autonomous Car – Entire System

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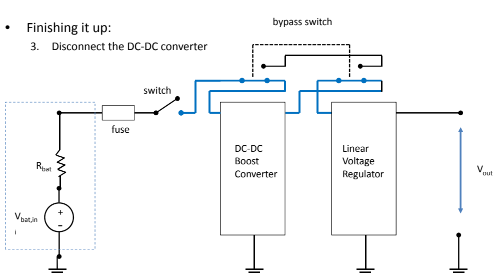

Summary: Power Supply for Autonomous Car

- 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