EECS192 Lecture 9
Motor Drive Introduction
Mar. 16, 2021

Topics

- Checkpoint 7: Step+ telemetry
- Robust wiring
- Quiz 2- motor model discussion
- HW 2 Simulation (due Fri 4/2)
- Progress report (due Fri 4/9)
- Motor Drive- Basic
- Quiz3- MOSFET 3/30
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- Control Fundamentals

Checkpoint 7: Telemetry+ Step Response

Set up a step track. Suggest 1 m before step, 1 m after step (0.5m+0.5m ok). The step should be 15 cm to the right or left.

C7.1 Basic step response. Live demo: show car drive past step and get back on track. Stream state data over UDP for this run:

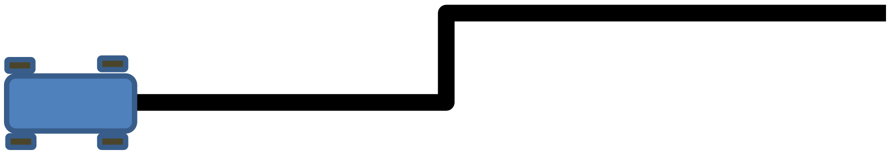
- i) timestep (seconds)
- ii) lateral error (cm or m)
- iii) estimated velocity (m/s)
- iv) commanded steering angle (rad or deg) and commanded ESC

C7.2 Plot state data with **labelled** axes. Report controller parameters used.

C7.3. Repeat C7.1 but with a better tuned or improved controller.

C7.4 Plot state data from C7.3 with **labelled** axes. Report controller parameters used.

C7.5 All members must fill out the checkpoint survey before the checkoff close. Completion is individually graded.



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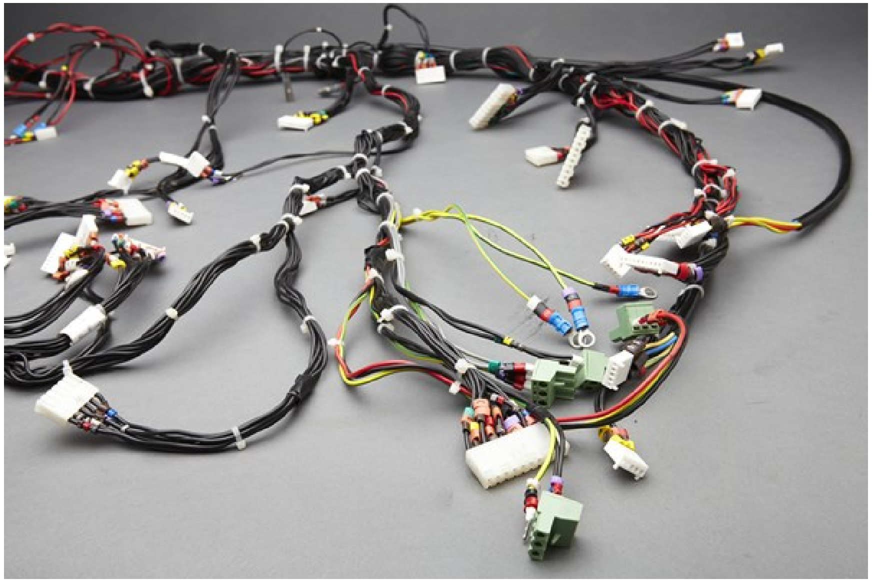
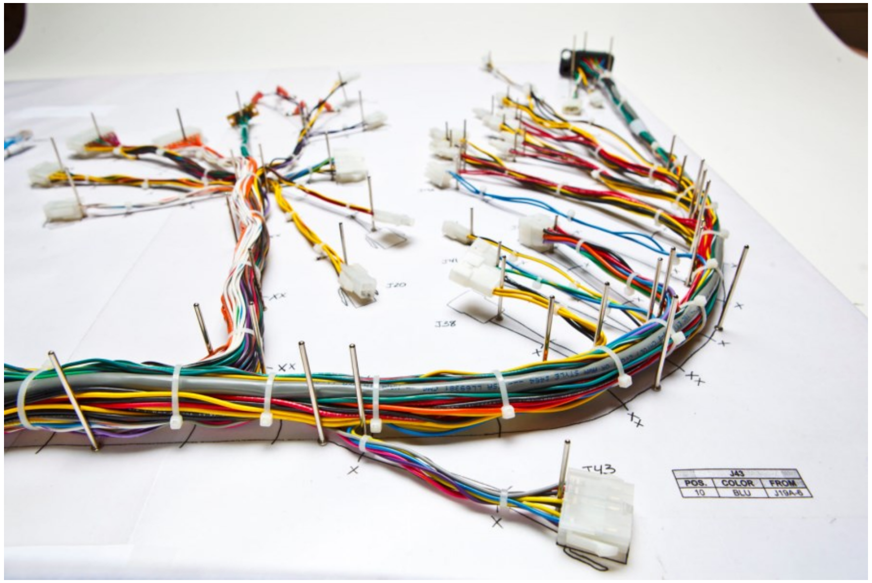
Robust Wiring



www.Harnesscable.com



www.saltlakecable.com

Flex vs stranded

A STUDY OF FATIGUE PROPERTIES 595

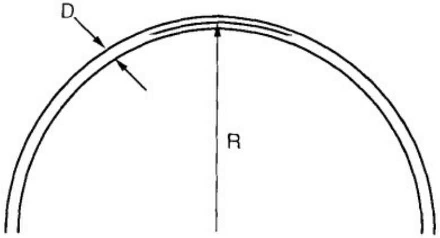


Figure 3. Test loop. This section of wire is subject to pure bending deformation as the wire rotates. R is the radius of curvature of the loop. D is the diameter of the wire or cable.

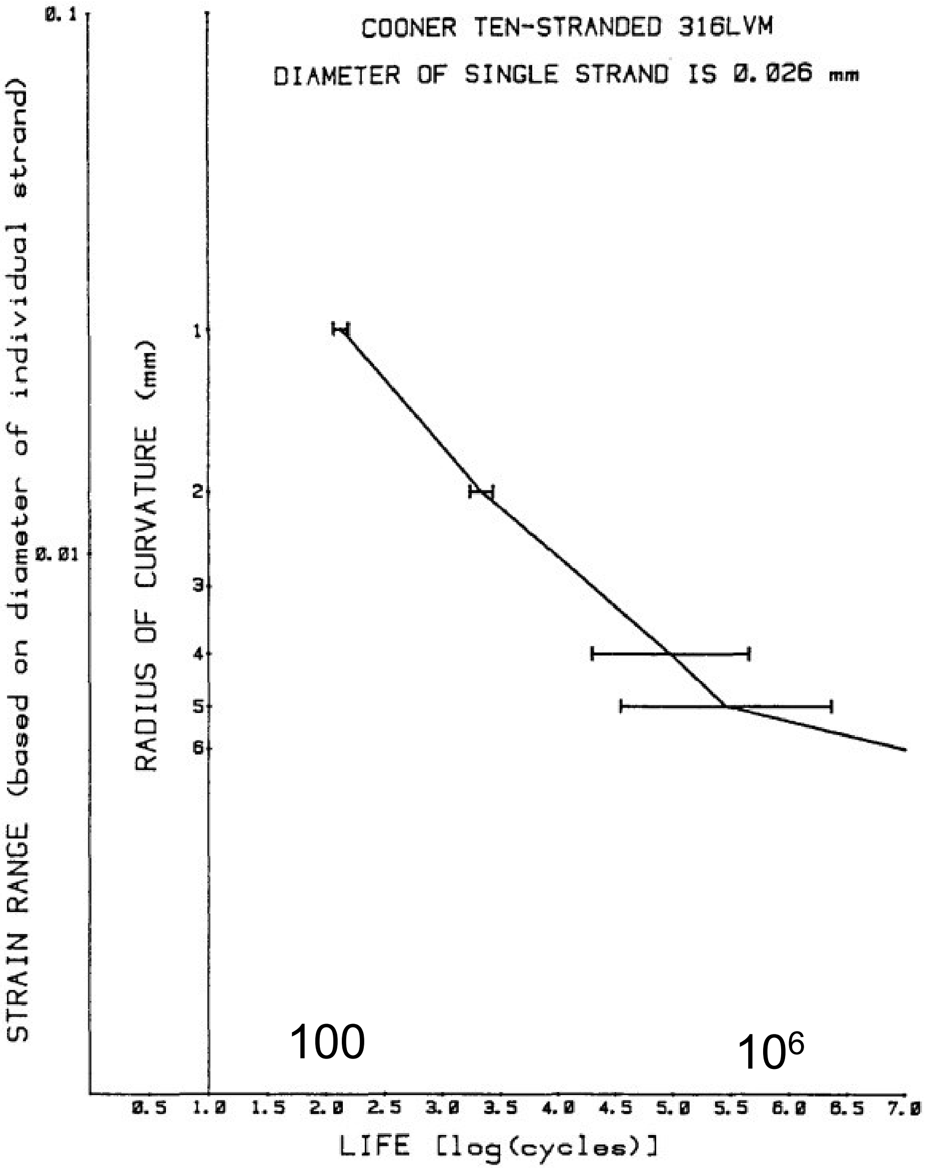


Figure 12. Strain range vs. fatigue life for Cooner ten-stranded 316LVM stainless steel multi-stranded wire.

``A study of the fatigue properties of small diameter wires used in intramuscular electrodes'' *Journal of biomedical materials research.* 1991 May;25(5):589-608.

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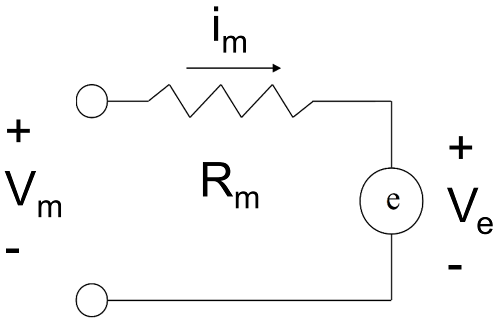
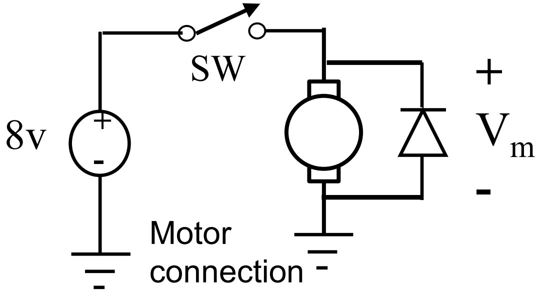
EE192 Spring 2021 Quiz 2

Consider a DC permanent magnet motor (as used in your car). The car is initially at rest. The motor is connected as shown below. Neglect battery and switch resistance. Neglect motor inductance. Assume diode is ideal. Assume motor resistance = 0.2 ohm, and that the car accelerates to 4 m/s in 2 seconds. Assume back EMF constant is 1V/(m/s). Assume time constant for deceleration is 1 second. Switch turns on at 0 sec, off at 2 sec.

Complete the sketches below for motor current i_m, motor voltage V_m, and car velocity.

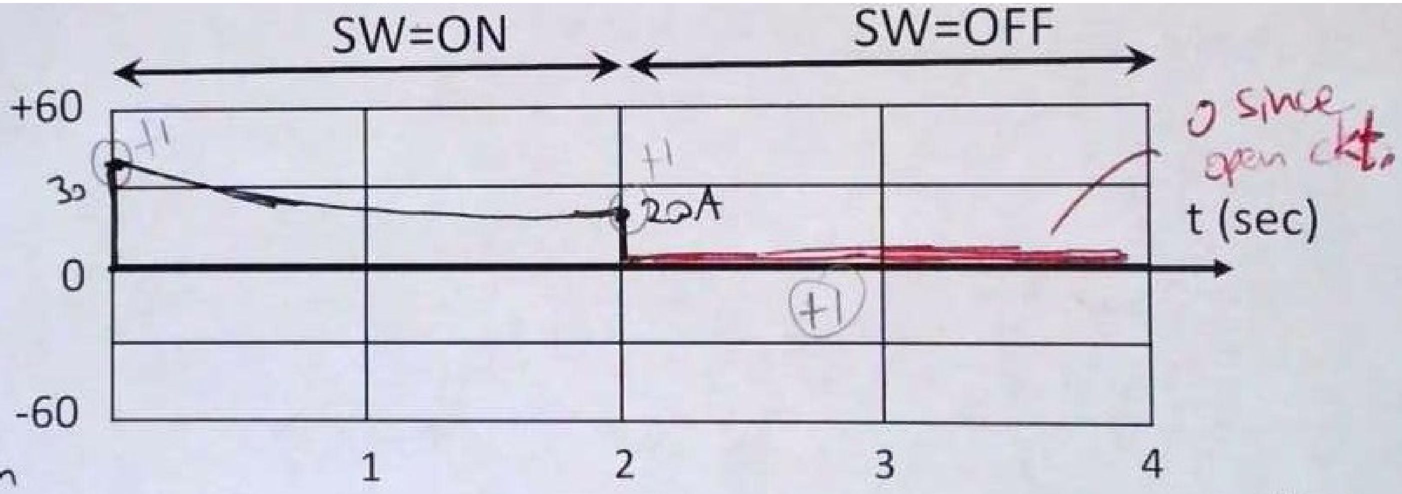




$\frac{8V}{0.2\Omega} = 40A$

+3

$\frac{8V - K_e\dot{\theta}_m}{0.2\Omega} = 40A - 5\dot{\theta}_m$



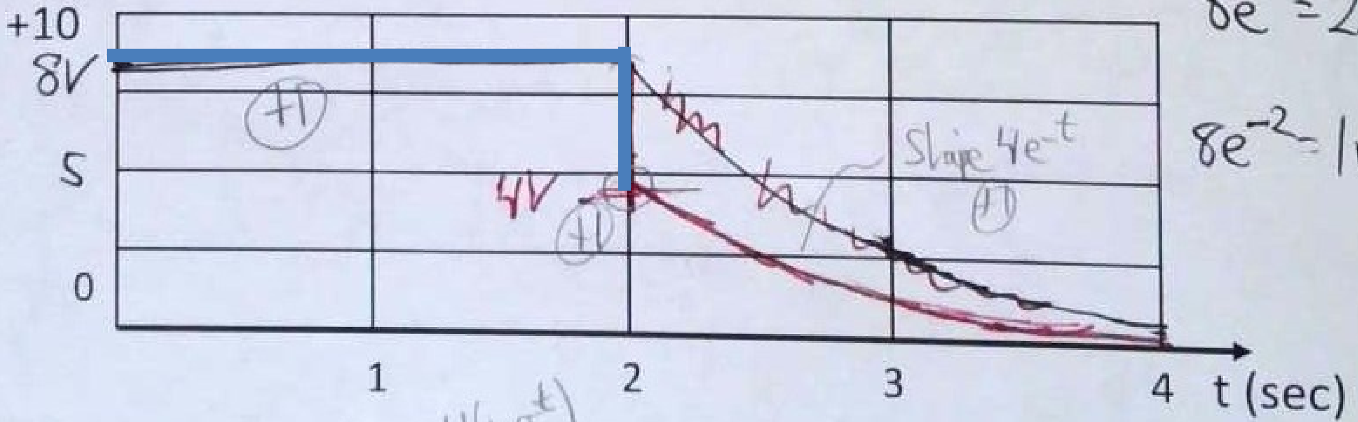
+3

$t > 2$:

$V_m = K_e\dot{\theta}_m$

$8e^{-1} = 2.9V$

$8e^{-2} = 1V$



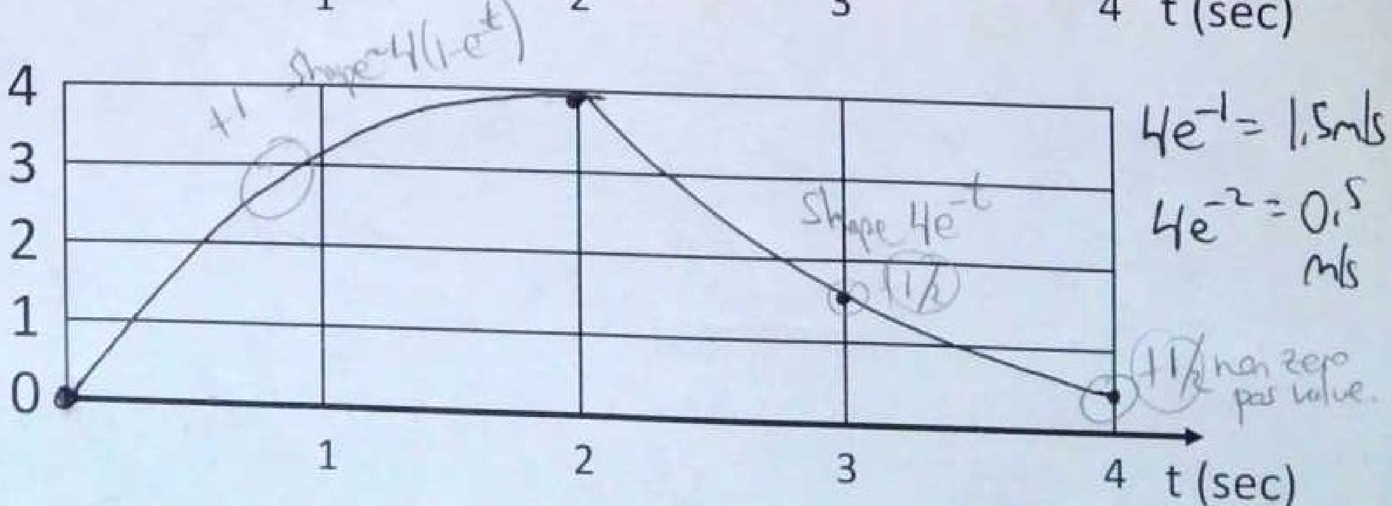
+2

$\dot{\theta}_m(0) = 0\,m/s$

$\dot{\theta}_m(2) = 4\,m/s$

$4e^{-1} = 1.5\,m/s$

$4e^{-2} = 0.5\,m/s$



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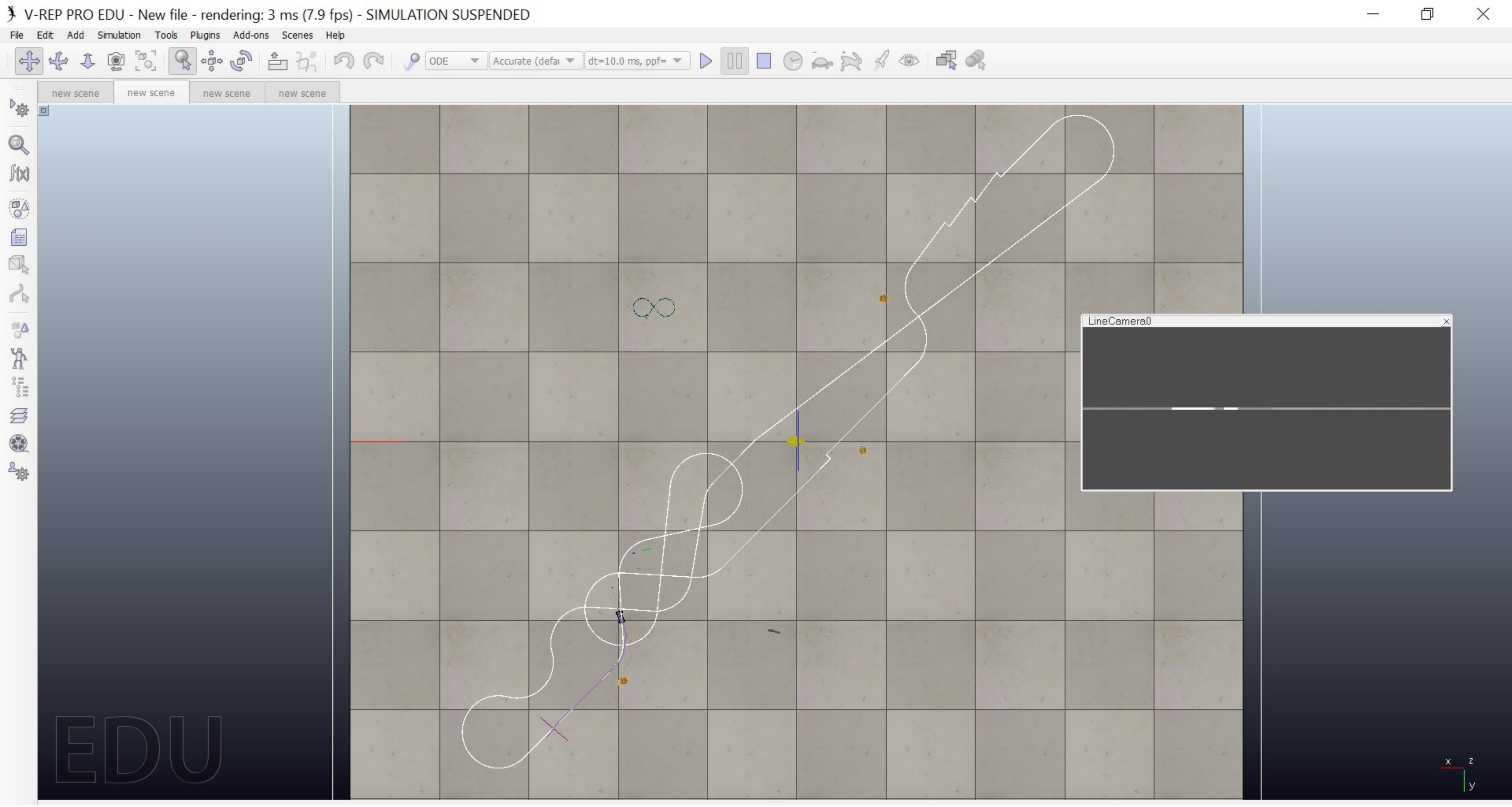
V-rep simulation- HW2



V-REP PRO EDU - New file - rendering: 3 ms (7.9 fps) - SIMULATION SUSPENDED

ODE

Accurate (defai

dt=10.0 ms, ppf=

demo

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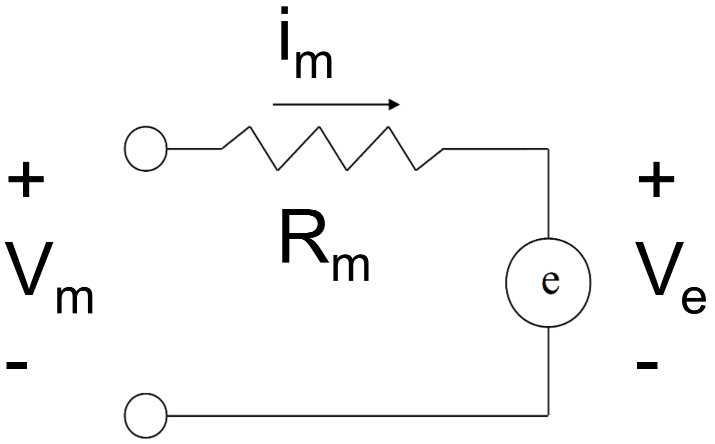
Progress Report Due Fri 4/9

https://inst.eecs.berkeley.edu/~ee192/sp21/docs/progrpt.pdf

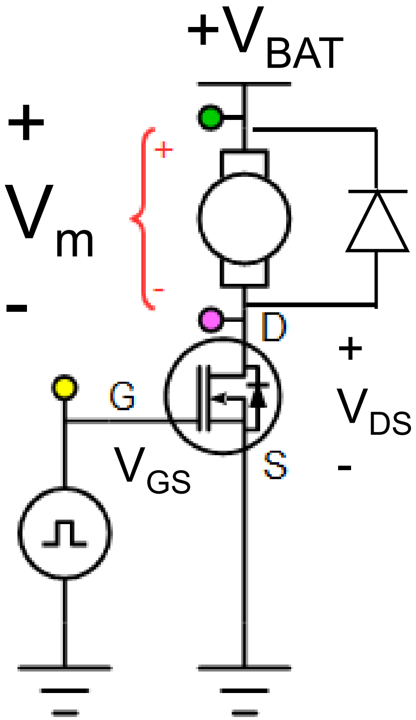
Motor Electrical Model



Motor Electrical Model
Back EMF
Motor electromechanical behavior

Also- see motor worksheet……

$$i_m = \frac{V_{BAT} - k_e \dot{\theta}_m}{R_m}$$



Motor Resistance?
Peak current?

Conclusion:
$\langle i_m \rangle = ?$

MOSFETs and motor drive

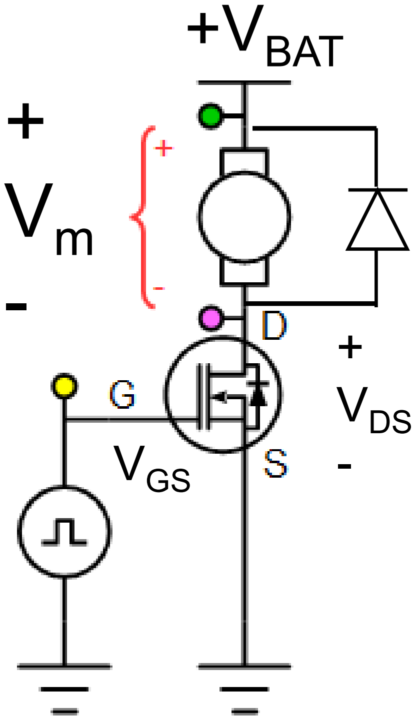
Given: Rm = 0.1 ohms, Vbatt = 7.2 V, Rbat = 0.

Vds = ? ➔ Ids = ? amps

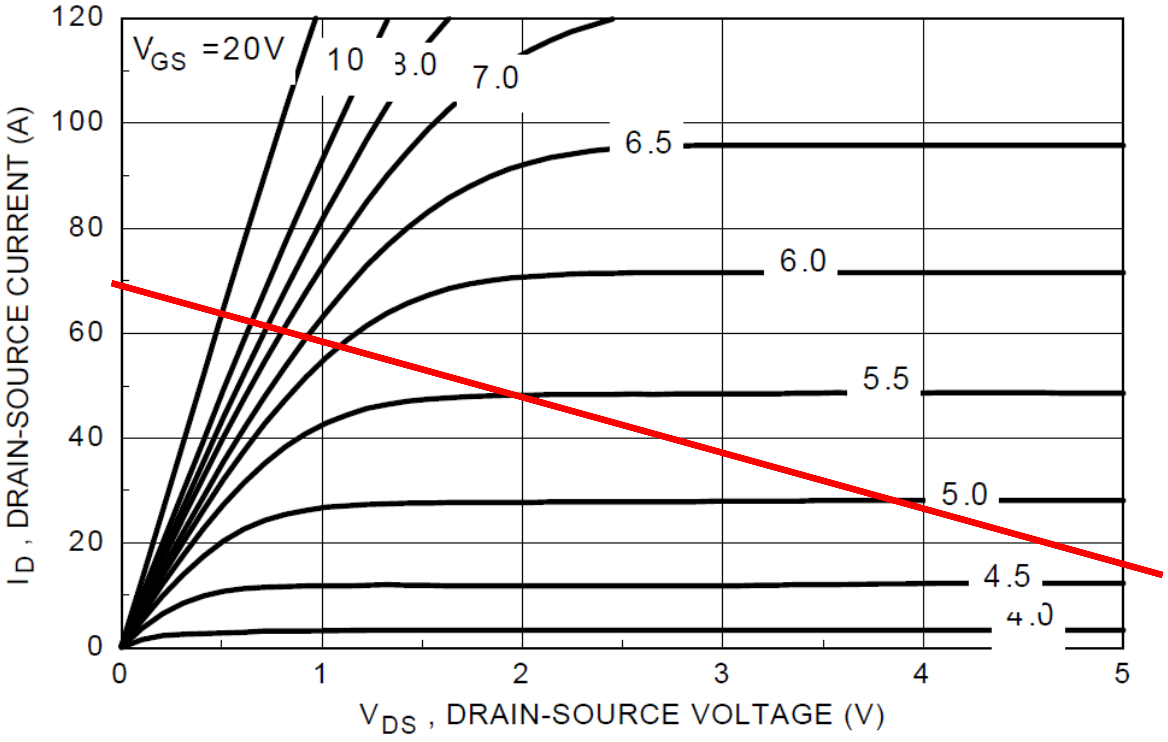
(LiPo 11 V!)

G = gate
D = Drain
S = Source

VDS=3.6V, IDS=?



Load line



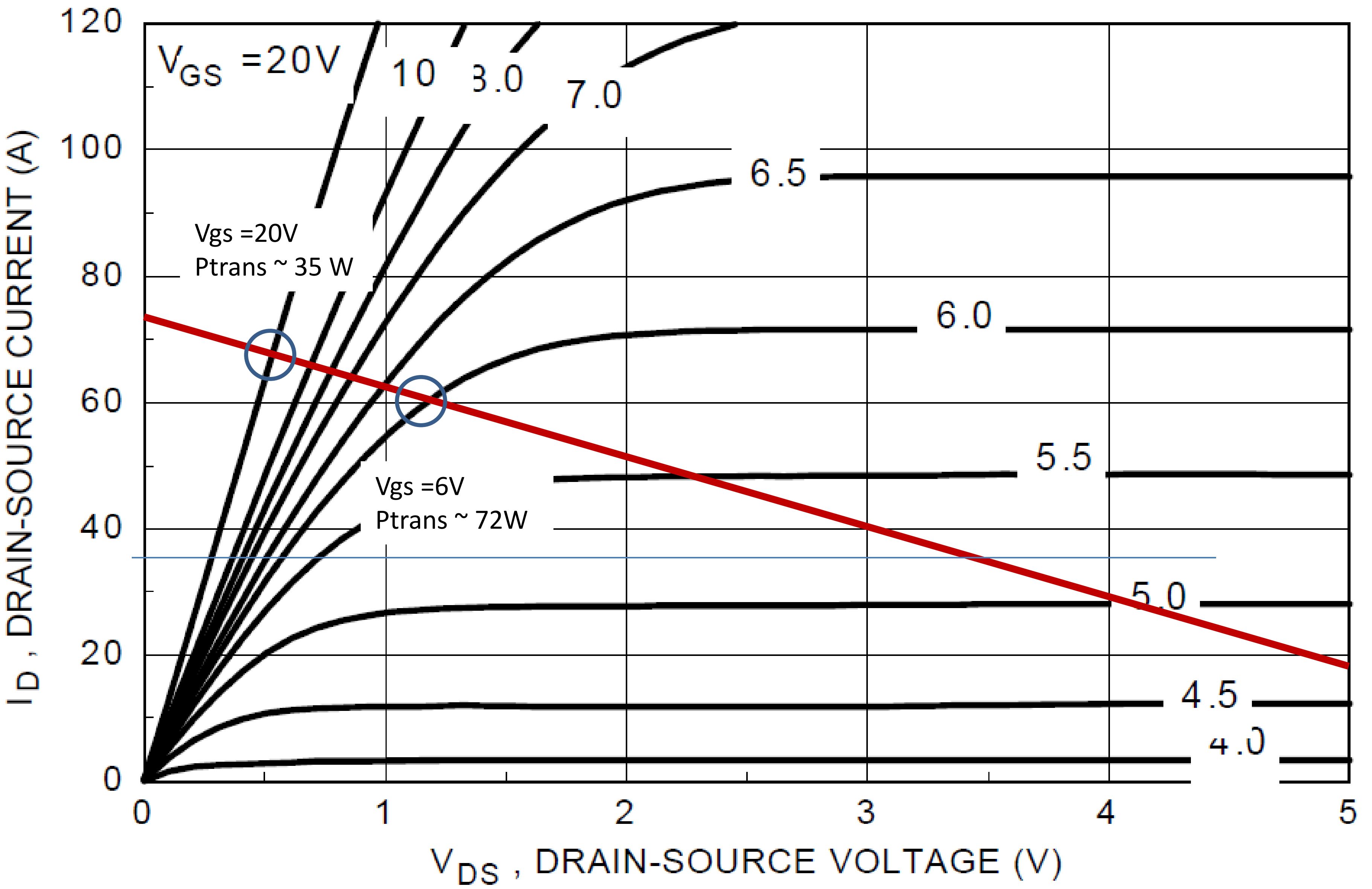
Driving MOSFETs and motor

Rm = 0.1 ohms, Vbatt = 7.2 V, Rbat = 0.

Vds = 3.6V ➔ Ids = (7.2-3.6V)/(0.1 ohm) = 36 amps

Key design points:

1) High Vgs better than low Vgs
2) Switch quickly
3) Make sure Vs=0 (big ground)



Vgs =20V
Ptrans ~ 35 W

Vgs =6V
Ptrans ~ 72W

Example Quiz 3 question

Consider the NMOS motor drive shown below:

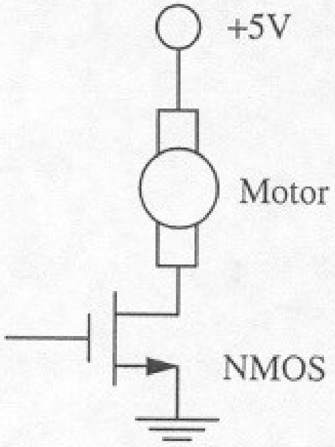


Figure 1

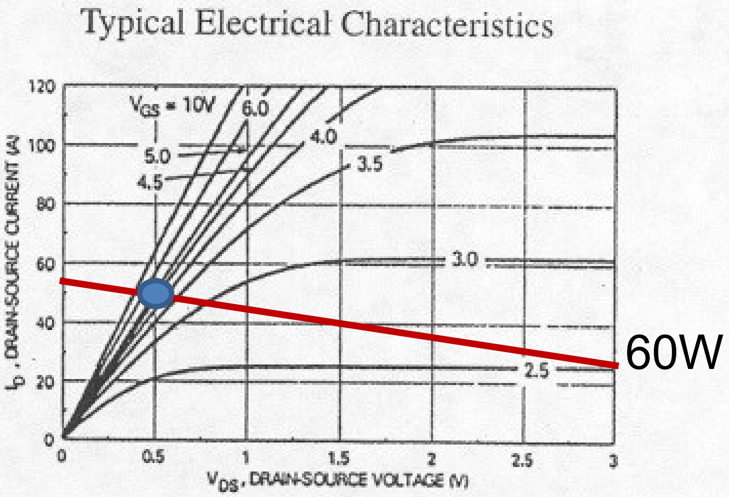


Figure 2: On-region Characteristics

The motor resistance is 0.1 ohm. Recall $P = I^2R$, $P = VI$. Assume the motor is stalled.

[4 pts.] a) Given that the NMOS transistor is able to dissipate 30 Watts, estimate the minimum V_{GS} required to prevent NMOS failure.

VDS=0.5V, IDS=42A. Ptrans=21W, Pmotor=(42A)(4.5V)

[4 pts.] b) What is the efficiency $\left(\frac{P_{\text{motor}}}{P_{\text{motor}} + P_{\text{transistor}}}\right)$ of the circuit when $V_{GS} = 5\text{V}$? 90%

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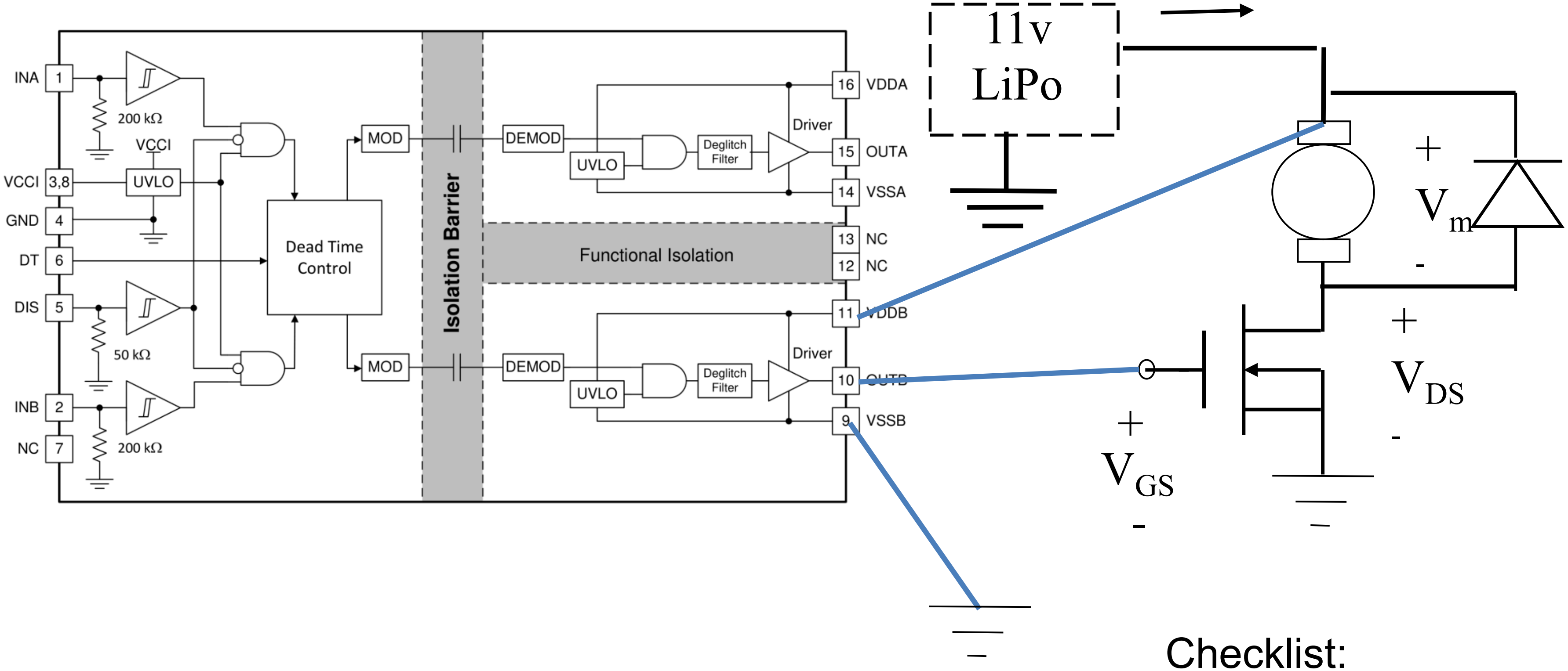
Motor Drive with UCC21222 gate driver

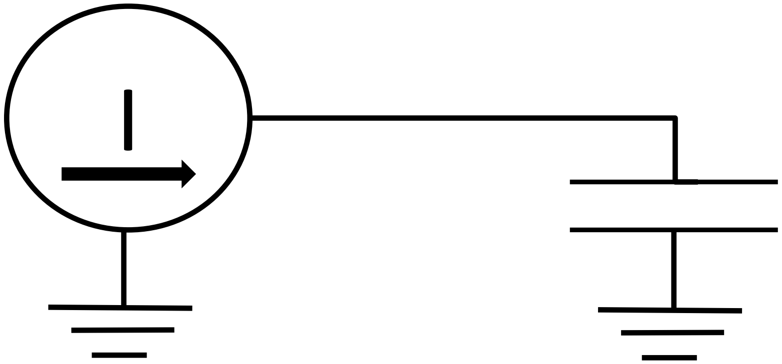


Details On board….

Checklist:

1) Emergency stop
2) Reset Protection
3) Snubbing

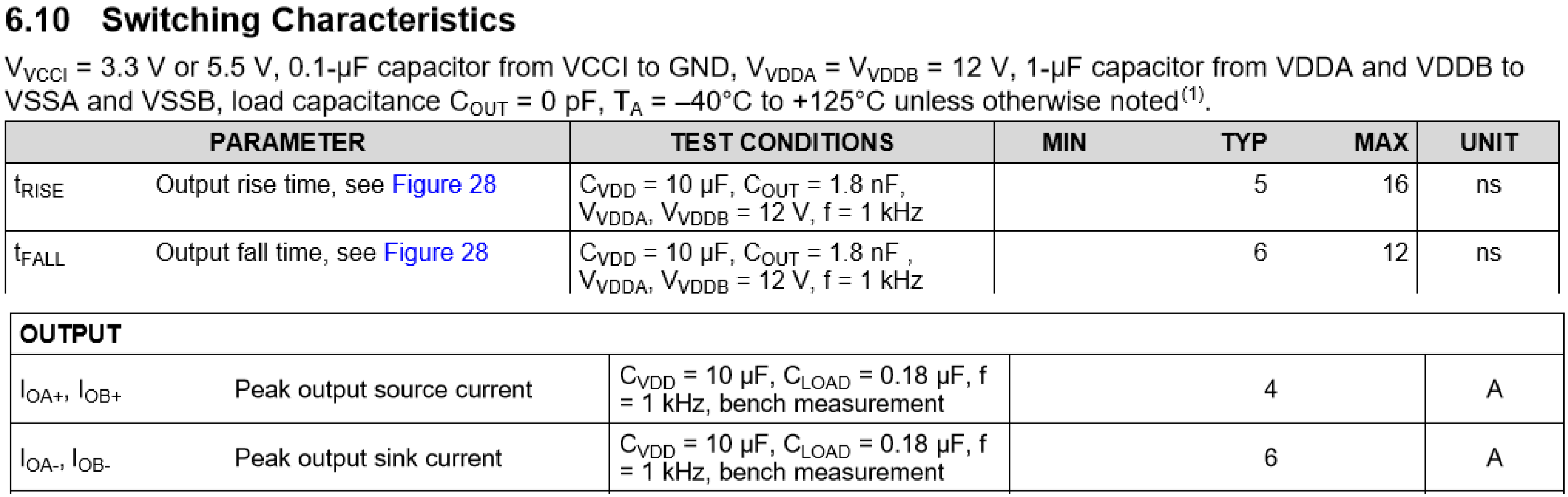
How to choose PWM frequency: UCC21222 driver constraint



I = C dv/dt

(on board)

Gate capacitance
5000 pF



6.10 Switching Characteristics

V_{VCCI} = 3.3 V or 5.5 V, 0.1-μF capacitor from VCCI to GND, $V_{VDDA} = V_{VDDB}$ = 12 V, 1-μF capacitor from VDDA and VDDB to VSSA and VSSB, load capacitance C_{OUT} = 0 pF, T_A = –40°C to +125°C unless otherwise noted(1).

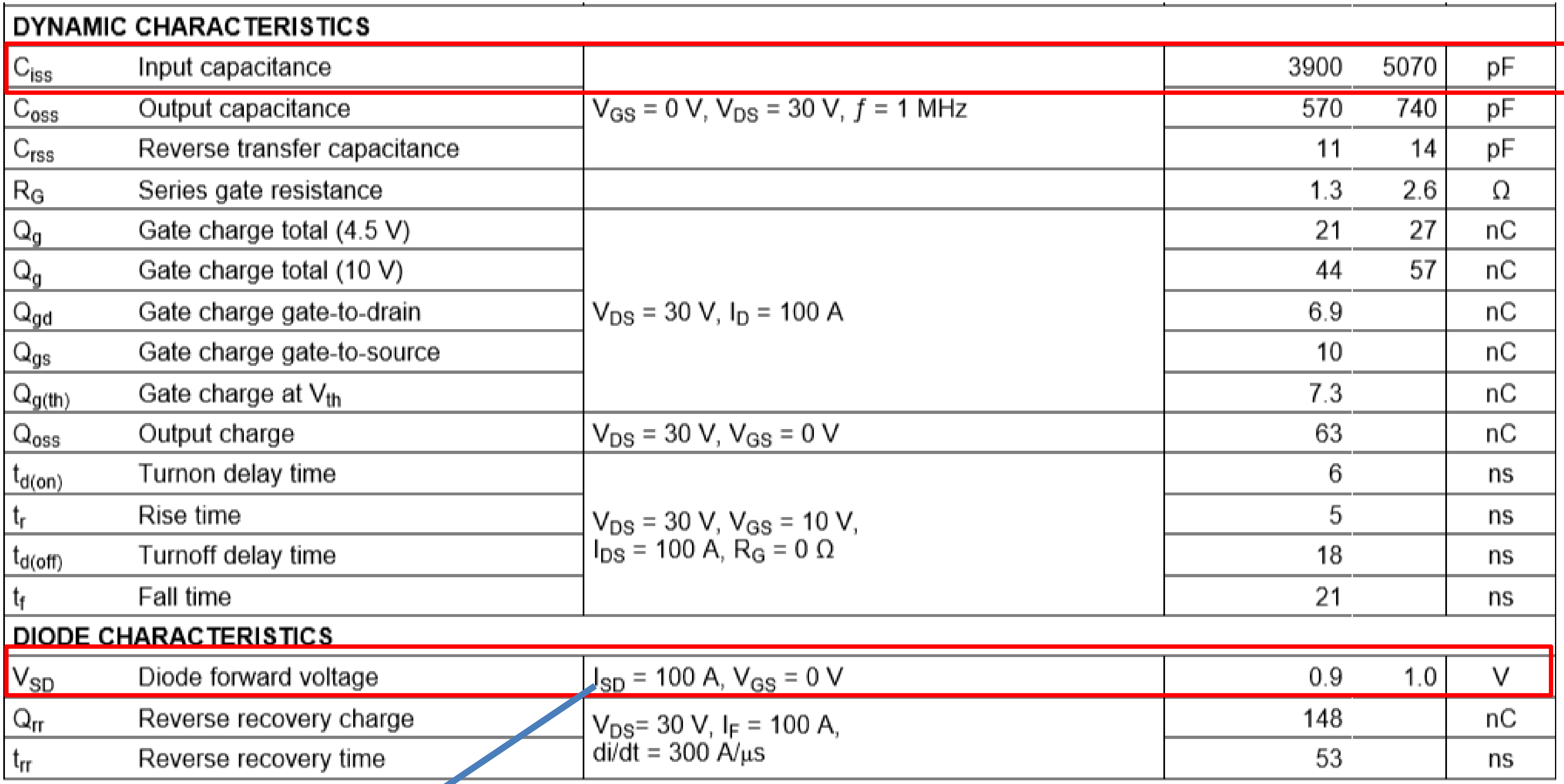
PARAMETER		TEST CONDITIONS	MIN	TYP	MAX	UNIT
t_{RISE}	Output rise time, see Figure 28	C_{VDD} = 10 μF, C_{OUT} = 1.8 nF, V_{VDDA}, V_{VDDB} = 12 V, f = 1 kHz		5	16	ns
t_{FALL}	Output fall time, see Figure 28	C_{VDD} = 10 μF, C_{OUT} = 1.8 nF , V_{VDDA}, V_{VDDB} = 12 V, f = 1 kHz		6	12	ns

OUTPUT						
I_{OA+}, I_{OB+}	Peak output source current	C_{VDD} = 10 μF, C_{LOAD} = 0.18 μF, f = 1 kHz, bench measurement		4		A
I_{OA-}, I_{OB-}	Peak output sink current	C_{VDD} = 10 μF, C_{LOAD} = 0.18 μF, f = 1 kHz, bench measurement		6		A

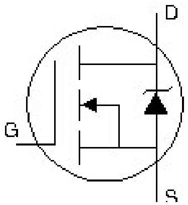
Driving MOSFETs and motor

CSD18542KTT Power MOSFET

How to choose PWM frequency?

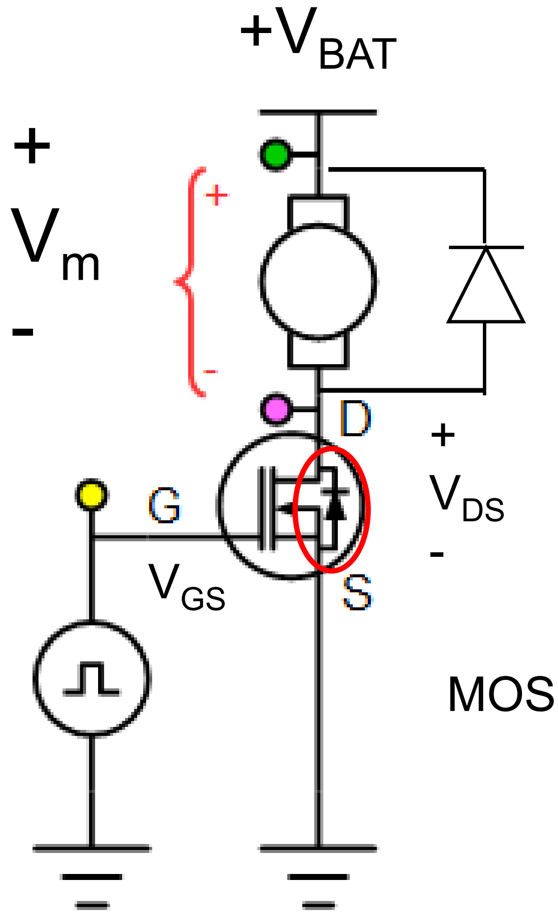


DYNAMIC CHARACTERISTICS					
C_{iss}	Input capacitance	V_{GS} = 0 V, V_{DS} = 30 V, f = 1 MHz	3900	5070	pF
C_{oss}	Output capacitance		570	740	pF
C_{rss}	Reverse transfer capacitance		11	14	pF
R_G	Series gate resistance		1.3	2.6	Ω
Q_g	Gate charge total (4.5 V)	V_{DS} = 30 V, I_D = 100 A	21	27	nC
Q_g	Gate charge total (10 V)		44	57	nC
Q_{gd}	Gate charge gate-to-drain		6.9		nC
Q_{gs}	Gate charge gate-to-source		10		nC
$Q_{g(th)}$	Gate charge at V_{th}		7.3		nC
Q_{oss}	Output charge	V_{DS} = 30 V, V_{GS} = 0 V	63		nC
$t_{d(on)}$	Turnon delay time	V_{DS} = 30 V, V_{GS} = 10 V, I_{DS} = 100 A, R_G = 0 Ω	6		ns
t_r	Rise time		5		ns
$t_{d(off)}$	Turnoff delay time		18		ns
t_f	Fall time		21		ns
DIODE CHARACTERISTICS					
V_{SD}	Diode forward voltage	I_{SD} = 100 A, V_{GS} = 0 V	0.9	1.0	V
Q_{rr}	Reverse recovery charge	V_{DS}= 30 V, I_F = 100 A, di/dt = 300 A/µs	148		nC
t_{rr}	Reverse recovery time		53		ns



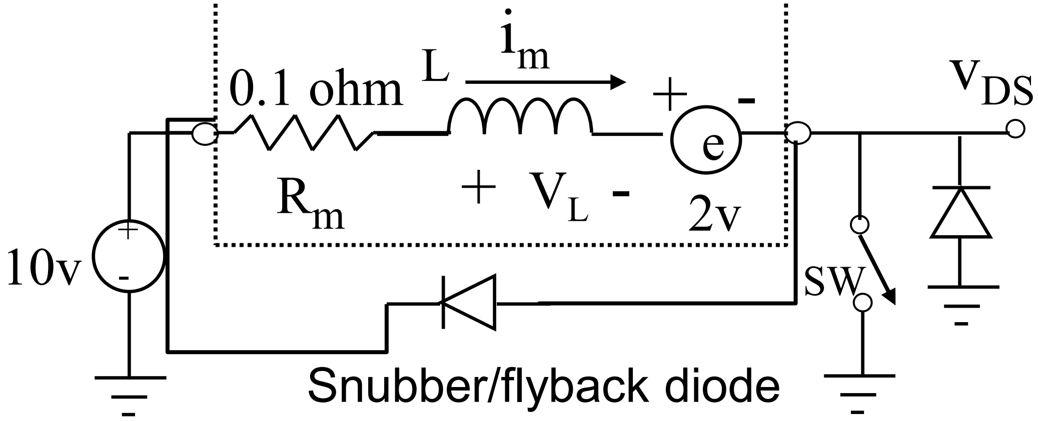
@10V , C=Q/V=57nC/10V = 5.7 nF

Low side motor drive



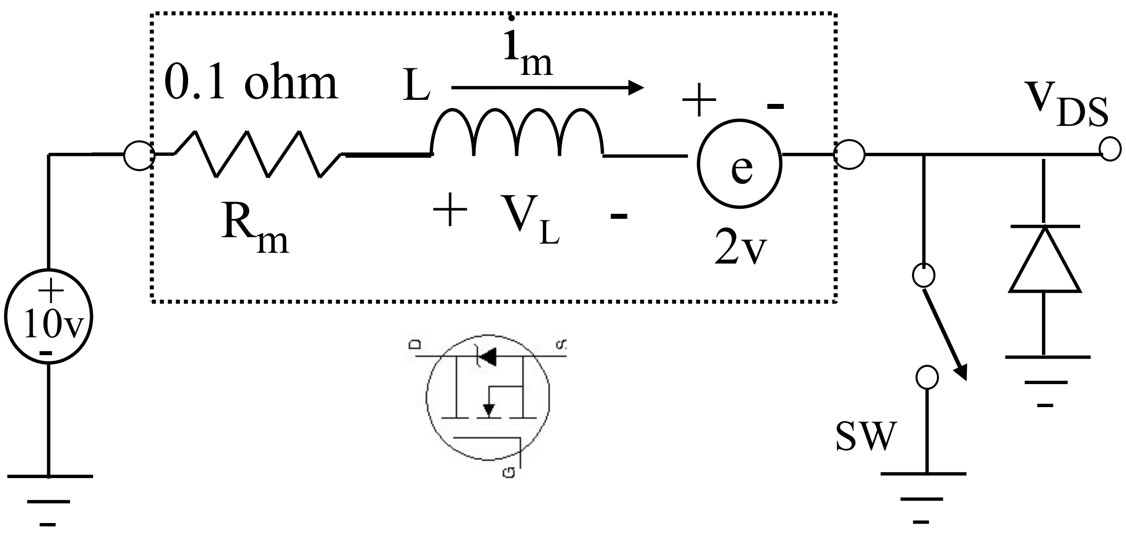
MOSFET body diode

What about motor inductance?

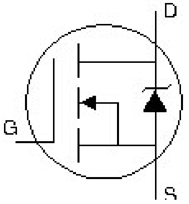


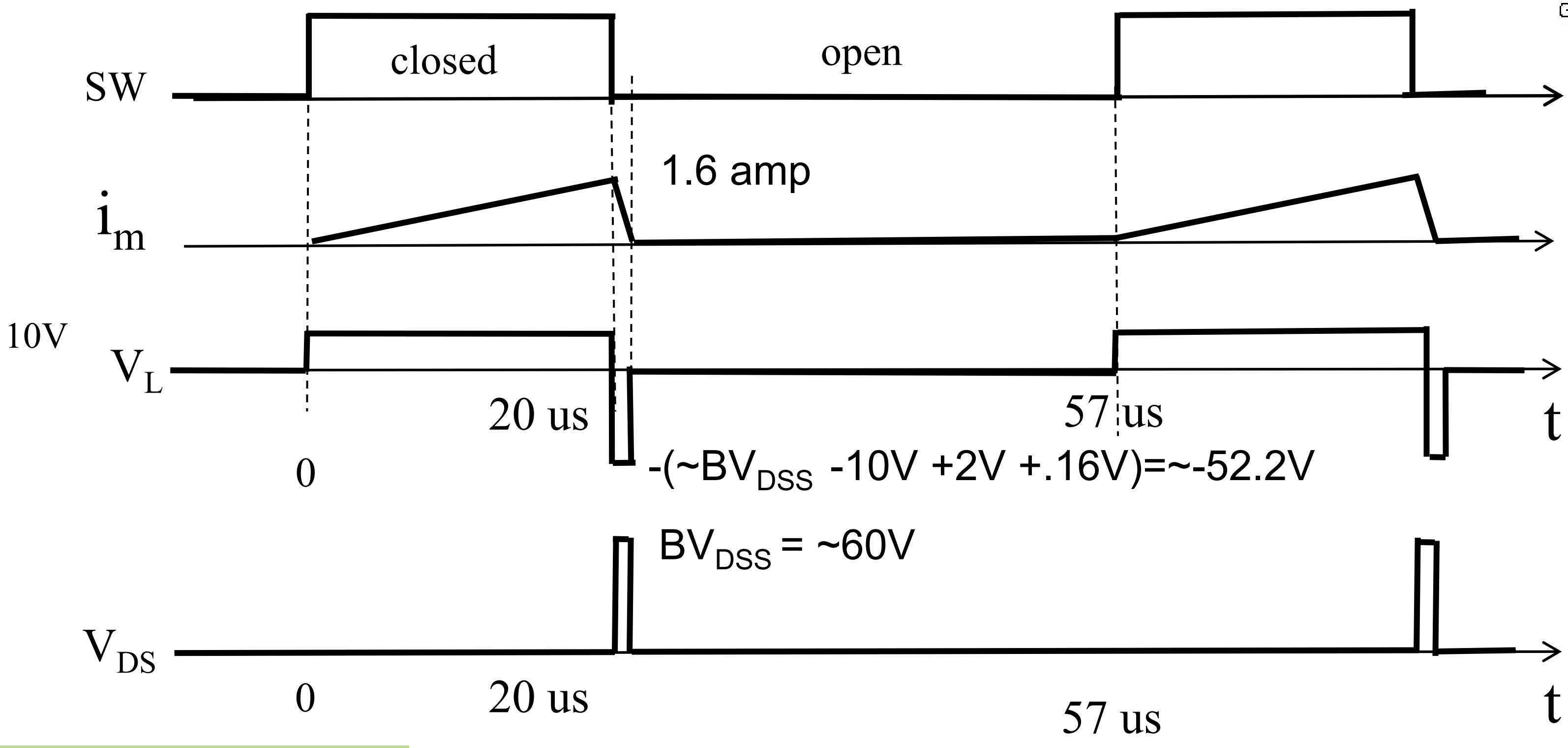
Snubber/flyback diode

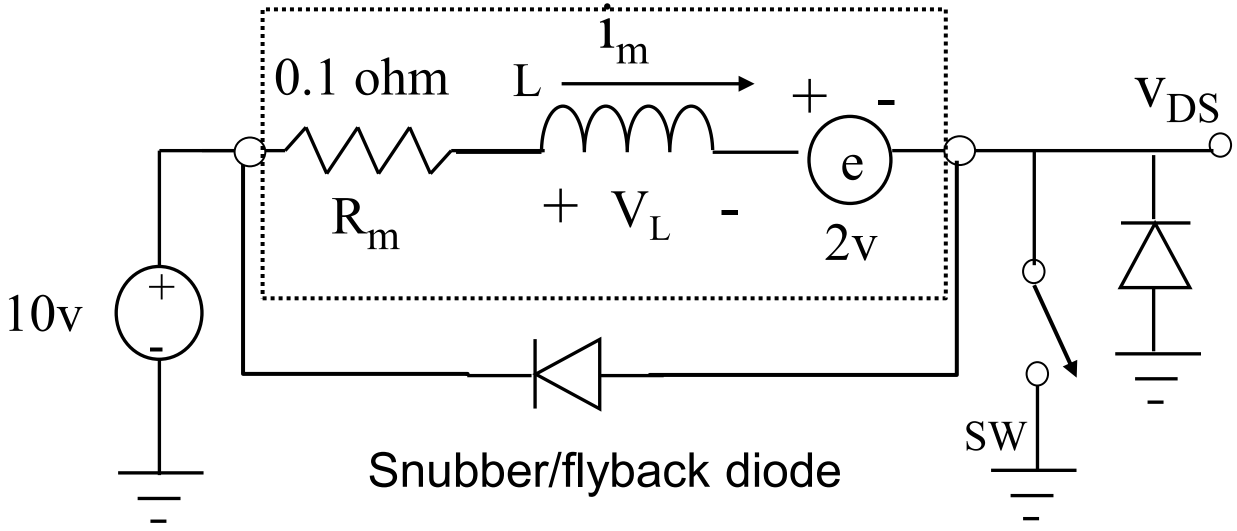
Motor+flywheel diode



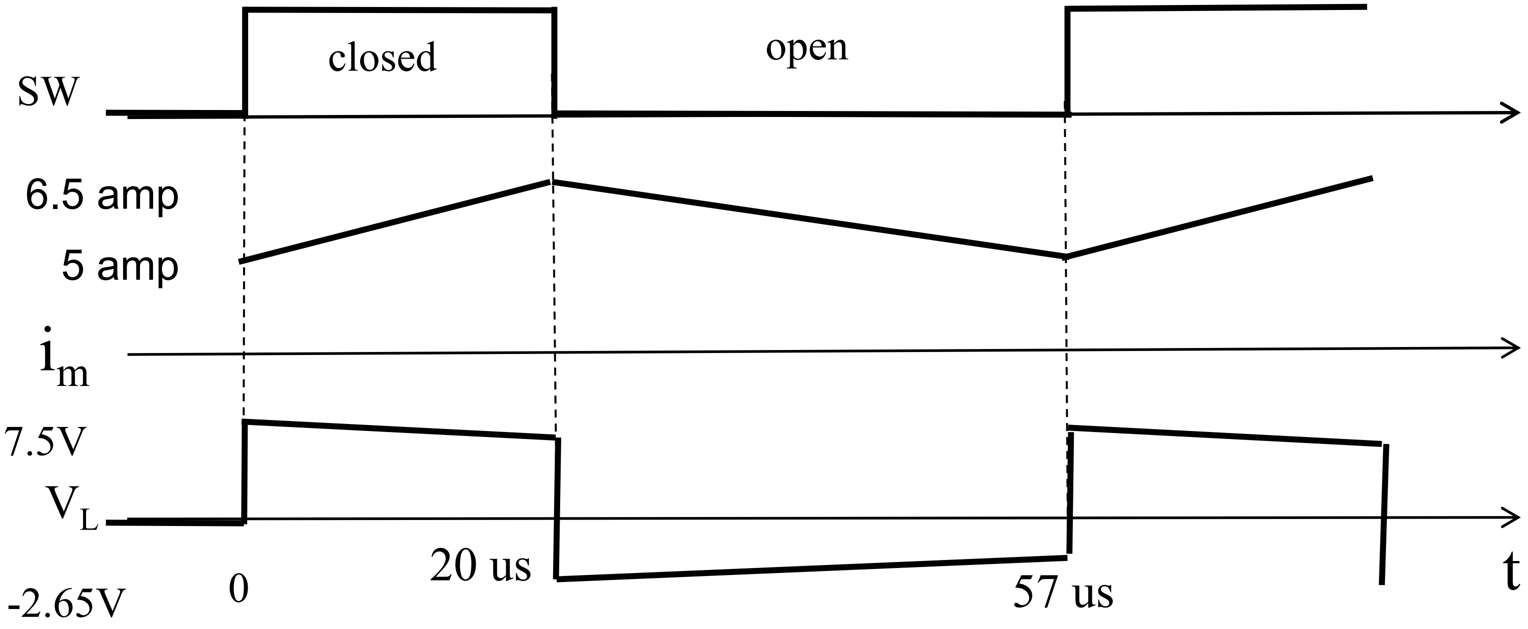
Assume ideal diode,
17 kHz
ideal switch, L= 100 μH.
Time constant τ = 1 ms.
Steady state, constant velocity.
Initial rate:
V/L= +8x10^4 amp/sec
NOTE: breakdown of body diode
BV_{DSS} = +60V (can damage device)







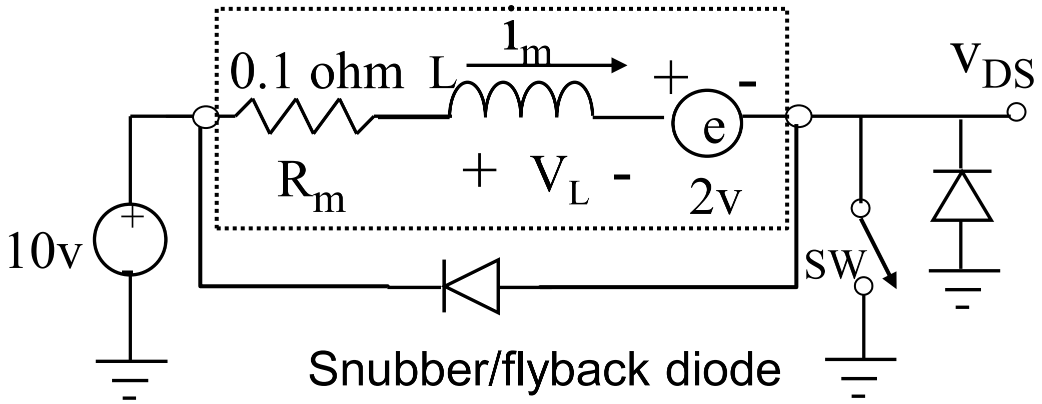
Assume ideal diode,
ideal switch, L= 100 μH.
Time constant τ = 1 ms.
Steady state,
constant velocity.
Assume i_{min} = 5 amp



L di/dt = 7.5V L di/dt = -2.65V

Note: 25 kHz PWM reduces peak current

Motor+flywheel diode



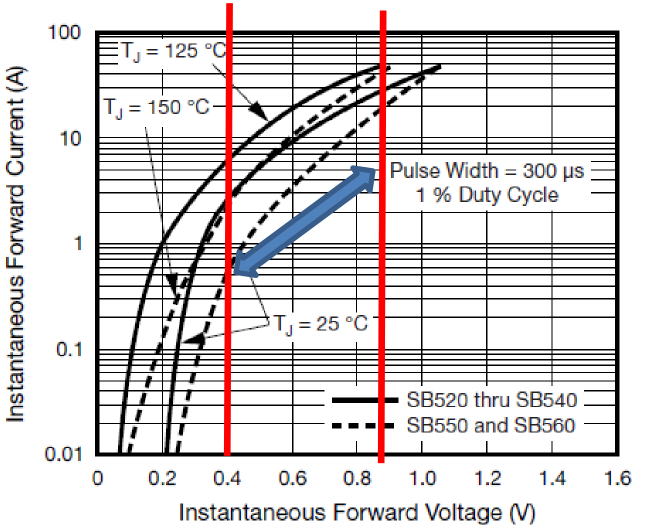
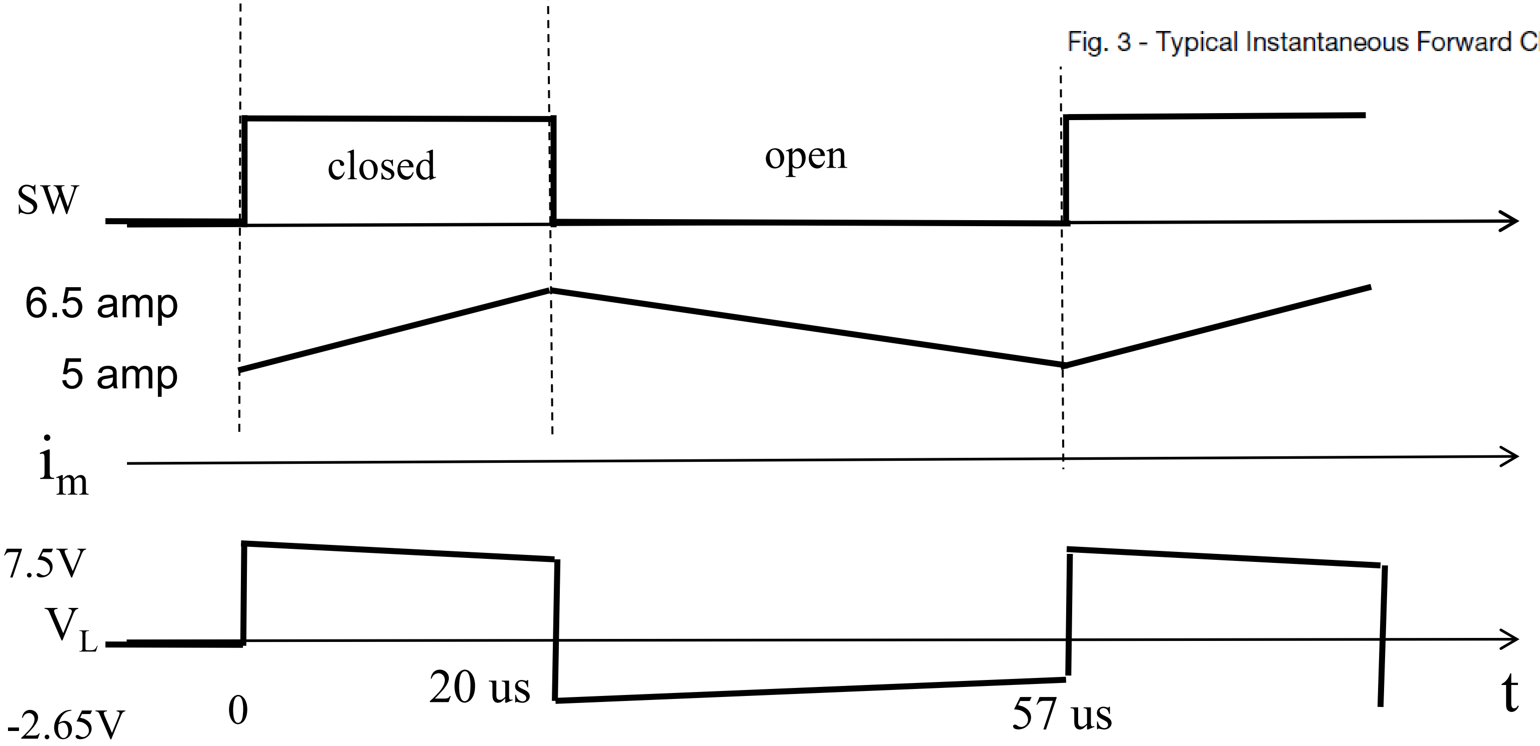
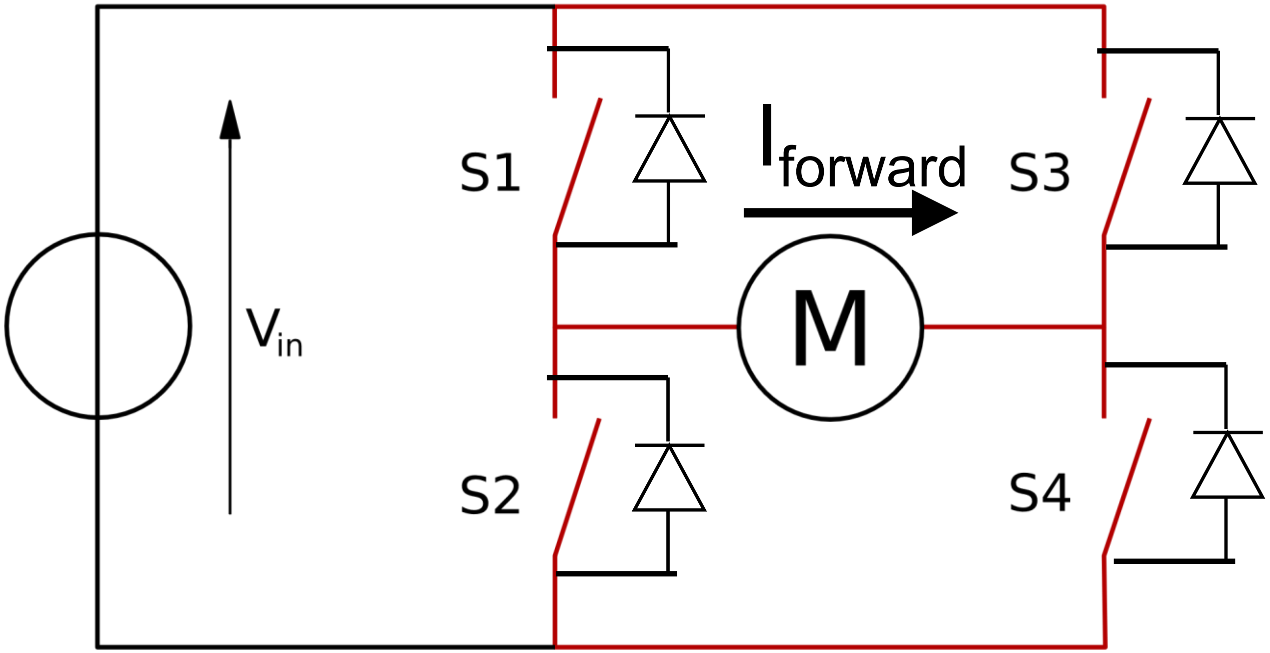


Fig. 3 - Typical Instantaneous Forward Characteristics

$$V_{DS} = 10V - V_{DIODE}$$



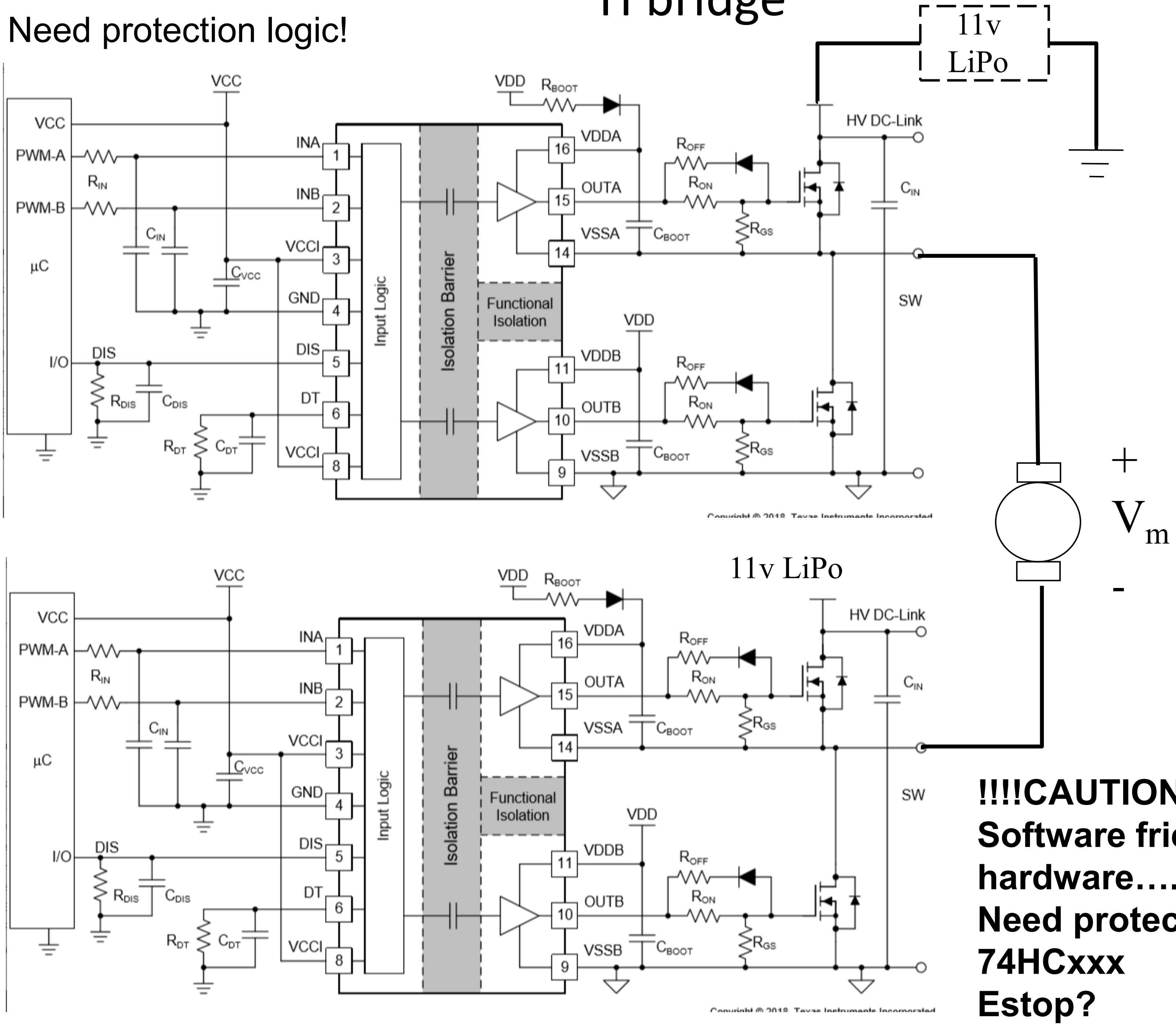
H Bridge Concept



S1	S2	S3	S3	Function?
Off	Off	Off	Off	
On	Off	Off	On	
Off	On	On	Off	
On	On	Off	Off	
On	Off	On	off	
Off	On	Off	on	

H bridge

Need protection logic!



!!!!CAUTION!!!!
Software fries hardware….
Need protection logic-
74HCxxx
Estop?

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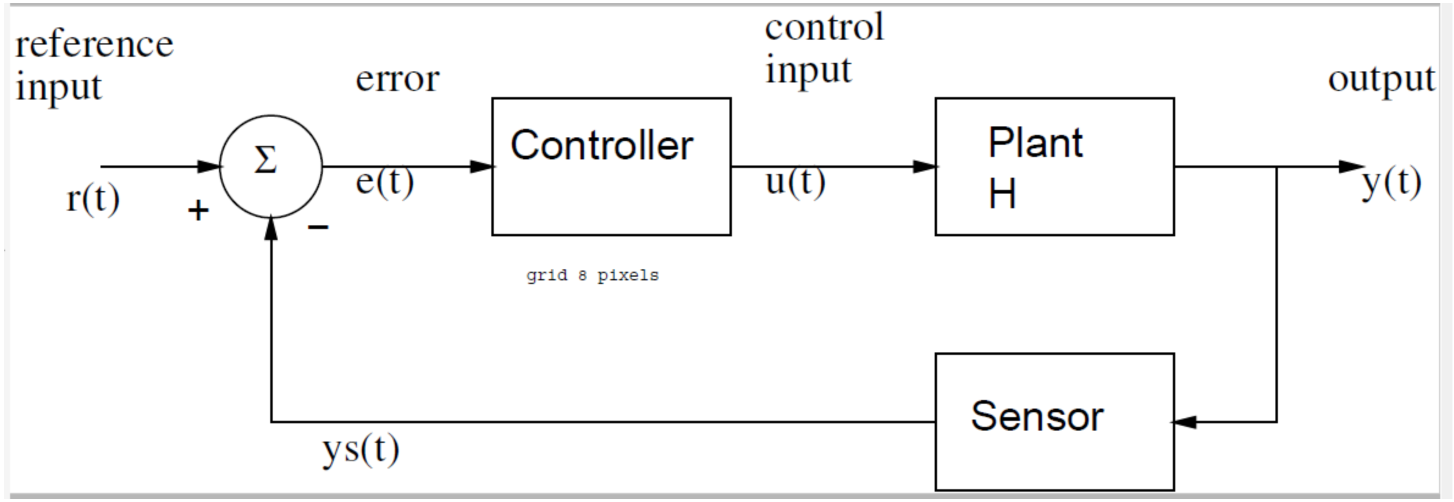
Control Synopsis



State equations: $\dot{x}(t) = ax(t) + bu(t)$

Output equations: $y(t) = cx(t) + du(t)$

Control Law (P): $u(t) = k_p e(t) = k_p(r(t) \ - \ y(t)).$

Control Synopsis

Control Law (P): $u(t) = k_p e(t) = k_p(r(t) \; - \; y(t)).$

New state equations:

$$\dot{x} = ax + bk_p e(t) = ax + bk_p(r - x) = (a - bk_p)x + bk_p r.$$

Zero Input Response (non-zero init condx):

$$x(t) = x(0)e^{(a-bk_p)t} \quad for \quad t \geq 0.$$

$a' = a - b\,k_p$ $\qquad$ $b' = b\,k_p$

Total Response (non-zero init condx) by convolution:

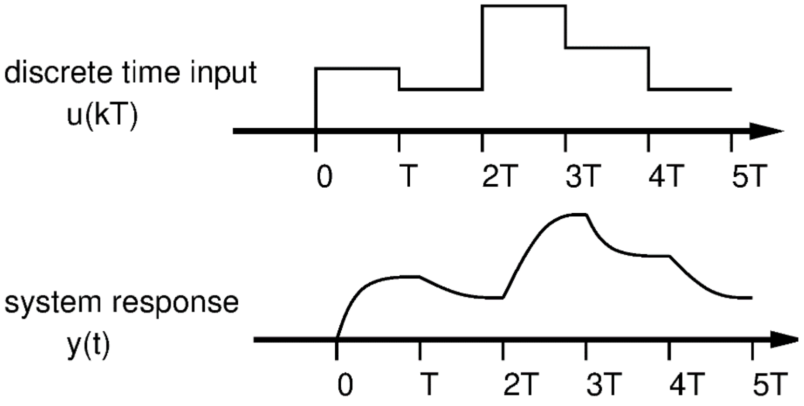
$$x(t_o) = e^{a't_o}x(0) + \int_0^{t_o} e^{a'(t_o-\tau)} b' r(\tau) d\tau \; . \tag{10}$$

Step Response (zero init condx) by convolution:

$$x(t_o) = b' \int_0^{t_o} e^{a't_o} e^{-a'\tau} d\tau \;\; = \;\; \frac{-b' e^{a't_o}}{a'} e^{-a'\tau}|_0^{t_o} \;\; = \frac{b'}{a'}(1 - e^{-a't_o}) \; . \tag{11}$$

Control Synopsis- Discrete Time

Superposition of Step Responses



$$x((k+1)T) = e^{a(k+1)T}x(0) + e^{a(k+1)T}\int_0^{(k+1)T} e^{-a\tau}bu(\tau)d\tau \ . \qquad (15)$$

$$x(kT) = e^{akT}x(0) + e^{akT}\int_0^{kT} e^{-a\tau}bu(\tau)d\tau \ . \qquad (14)$$

$$x((k+1)T) = e^{aT}x(kT) + e^{a(k+1)T}\int_{kT}^{(k+1)T} e^{-a\tau}bu(\tau)d\tau \ = e^{aT}x(kT) + \int_0^{T} e^{a\lambda}bu(kT)d\lambda \ , \ (16)$$

Control Synopsis- Discrete Time

$$G(T) \equiv e^{aT} \quad \text{and} \quad H(T) \equiv b \int_0^T e^{a\lambda} d\lambda \ . \tag{17}$$

State equations:

$$x((k+1)T) = G(T)x(kT) + H(T)u(kT) \tag{18}$$

Output equations:

$$y(kT) = Cx(kT) + Du(kT) \ . \tag{19}$$

Total Response (non-zero init condx) by convolution:

$$x(k) = G^k x(0) + \sum_{j=0}^{k-1} G^{k-j-1} H u(j) \ . \tag{23}$$

Control Synopsis- Discrete Time

Control Law (P): $U(kT) = k_p\,[r(kT) - x(kT)]$

New state equations:

$$x((k+1)T) = G(T)x(kT) + H(T)k_p(r(kT) - x(kT)) = [G - Hk_p]x(kT) + Hk_p r(kT)\ . \quad (24)$$

$$x((k+1)T) = [e^{aT} + \frac{k_p}{a}(1 - e^{aT})]x(kT) + Hk_p r(kT) \ = \ G' x(kT) + Hk_p r(kT) \ . \quad (25)$$

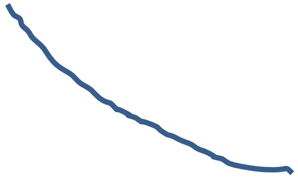
For stability:

$$|e^{aT} - \frac{k_p}{a}(e^{aT} - 1)| < 1. \quad (26)$$

Notes: stability depends on gain **and** T!

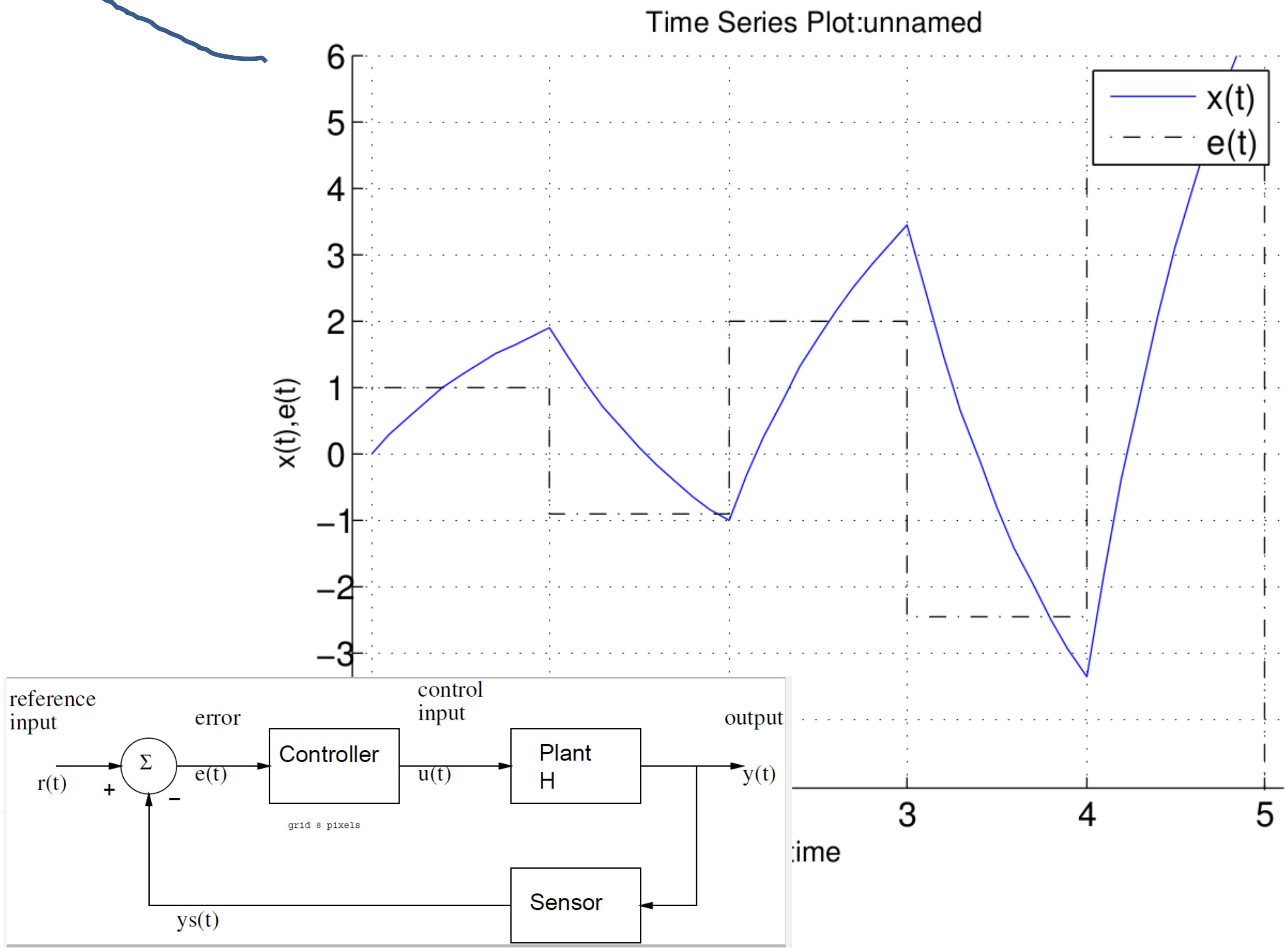
Discrete Time Control

e(t), u=kp e(t)



$u[k] = kp*(r[k]-x[k])$

Let $x[k] = y[k]$



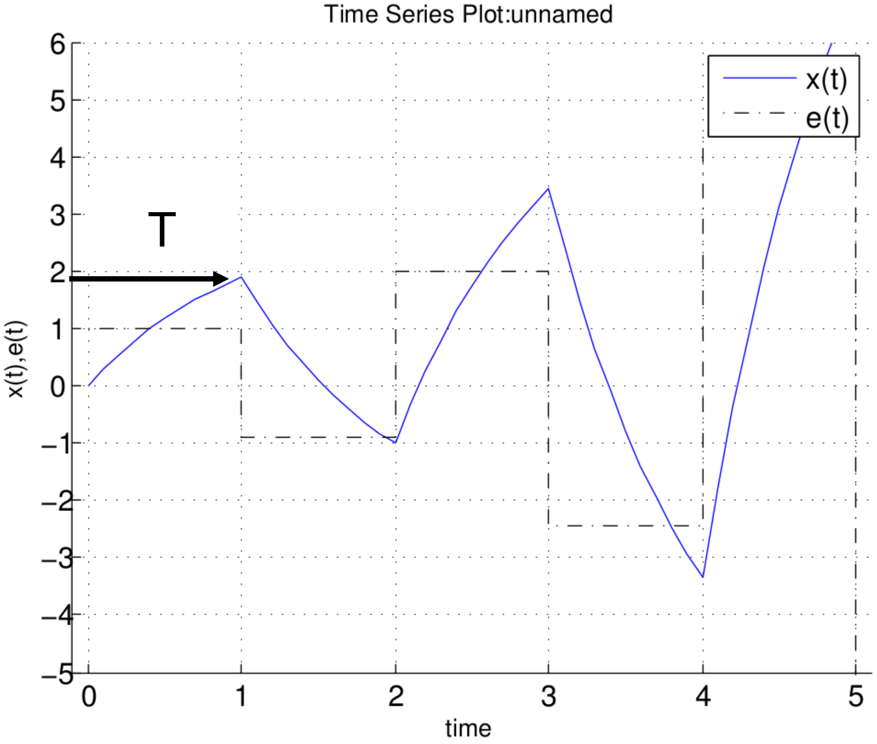
Example control- discrete time

First order CT system $\dot{x} = -x + u$

Let x = car velocity
Reference r=1 m/s unit step, k=3
e(t) = r(t) – x(t)
Let control input u[n]=3(r[n]-x[n]) = 3e[n],

Watch out for delay!
Watch out for excess gain!

t (sec)	x(t)	e(t) = r(t) - x(t)	u(t)
0^-	0	0	0
0	0	1	3
1	2	-1	-3
2	-1	2	6
3	3.5	-2.5	-7.5
4	-3.5	4.5	13.5



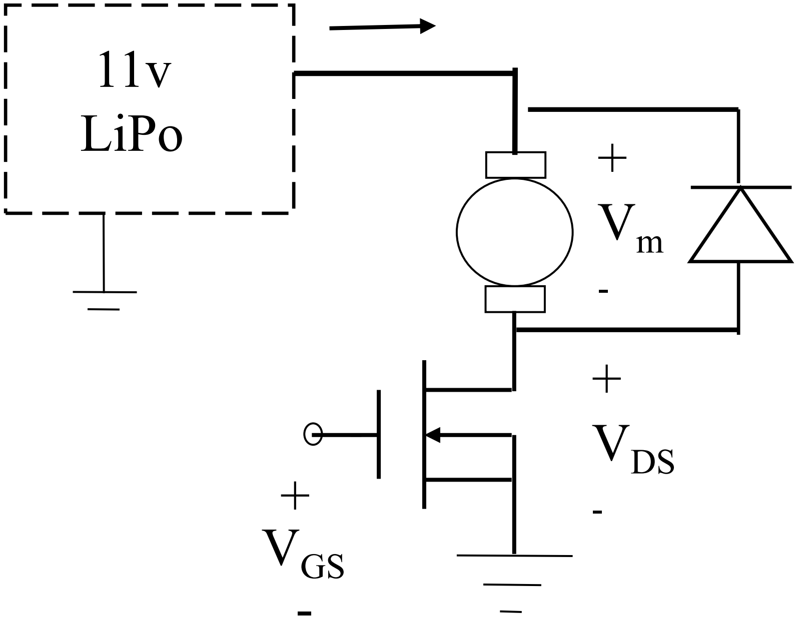
EECS192 Lecture 9
Motor Drive Introduction
Mar. 16, 2021

Topics

- ➡ Checkpoint 7: Step+ telemetry
- Robust wiring
- Quiz 2- motor model discussion
- HW 2 Simulation (due Fri 4/2)
- Progress report (due Fri 4/9)
- Motor Drive- Basic
- Quiz3- MOSFET 3/30
- Motor Drive- details
- Control Fundamentals

Extra Slides

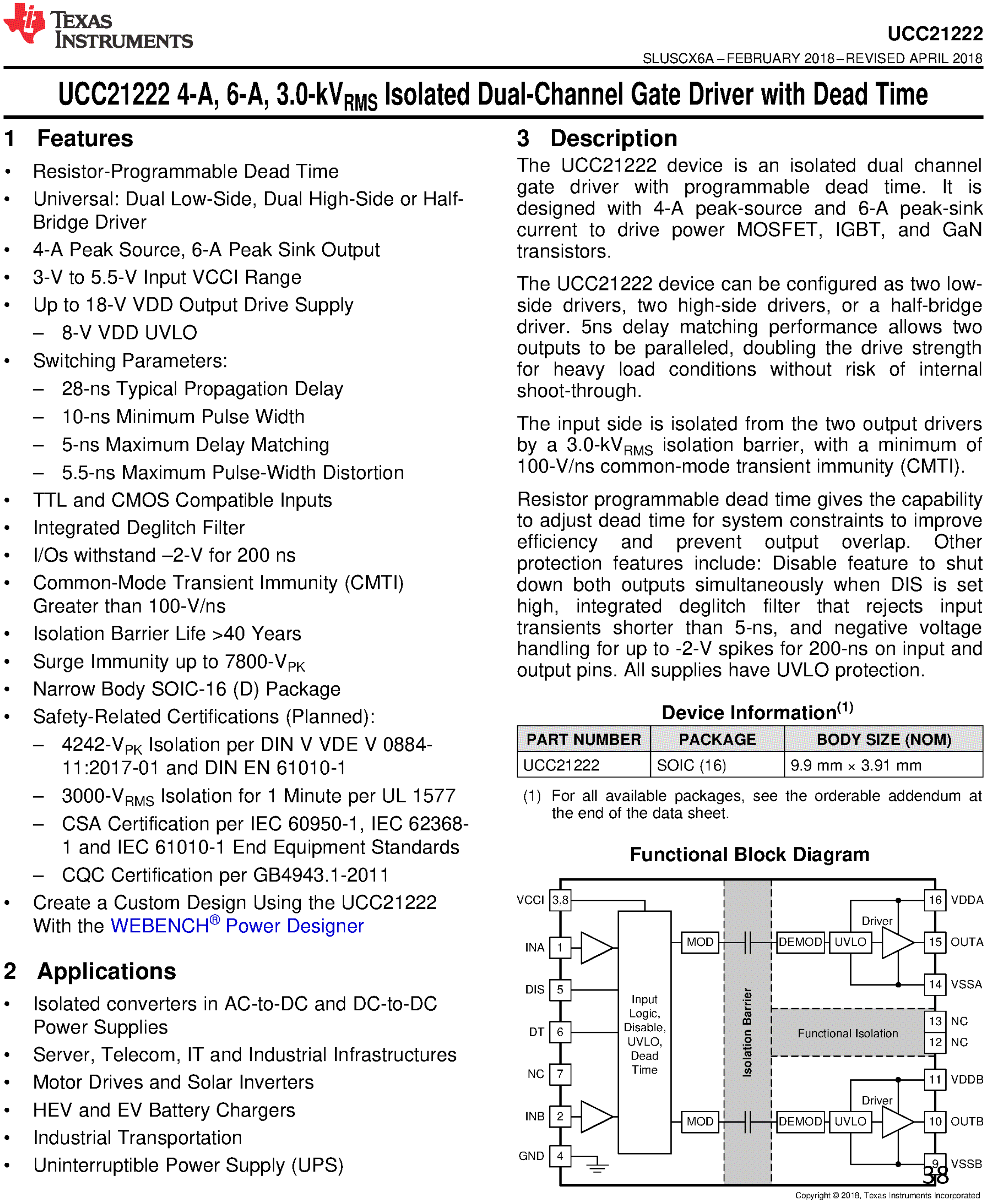
Wiring Notes: caution on Vgs



On board

Watch out for voltage drop in wires/PCB traces.
#22 wire: 50 mOhm/m
#12 wire: 5 mOhm/m

Driving MOSFETs and motor



TEXAS INSTRUMENTS

UCC21222

SLUSCX6A – FEBRUARY 2018 – REVISED APRIL 2018

UCC21222 4-A, 6-A, 3.0-kV$_{RMS}$ Isolated Dual-Channel Gate Driver with Dead Time

1 Features

- Resistor-Programmable Dead Time
- Universal: Dual Low-Side, Dual High-Side or Half-Bridge Driver
- 4-A Peak Source, 6-A Peak Sink Output
- 3-V to 5.5-V Input VCCI Range
- Up to 18-V VDD Output Drive Supply
  - 8-V VDD UVLO
- Switching Parameters:
  - 28-ns Typical Propagation Delay
  - 10-ns Minimum Pulse Width
  - 5-ns Maximum Delay Matching
  - 5.5-ns Maximum Pulse-Width Distortion
- TTL and CMOS Compatible Inputs
- Integrated Deglitch Filter
- I/Os withstand –2-V for 200 ns
- Common-Mode Transient Immunity (CMTI) Greater than 100-V/ns
- Isolation Barrier Life >40 Years
- Surge Immunity up to 7800-V$_{PK}$
- Narrow Body SOIC-16 (D) Package
- Safety-Related Certifications (Planned):
  - 4242-V$_{PK}$ Isolation per DIN V VDE V 0884-11:2017-01 and DIN EN 61010-1
  - 3000-V$_{RMS}$ Isolation for 1 Minute per UL 1577
  - CSA Certification per IEC 60950-1, IEC 62368-1 and IEC 61010-1 End Equipment Standards
  - CQC Certification per GB4943.1-2011
- Create a Custom Design Using the UCC21222 With the WEBENCH® Power Designer

2 Applications

- Isolated converters in AC-to-DC and DC-to-DC Power Supplies
- Server, Telecom, IT and Industrial Infrastructures
- Motor Drives and Solar Inverters
- HEV and EV Battery Chargers
- Industrial Transportation
- Uninterruptible Power Supply (UPS)

3 Description

The UCC21222 device is an isolated dual channel gate driver with programmable dead time. It is designed with 4-A peak-source and 6-A peak-sink current to drive power MOSFET, IGBT, and GaN transistors.

The UCC21222 device can be configured as two low-side drivers, two high-side drivers, or a half-bridge driver. 5ns delay matching performance allows two outputs to be paralleled, doubling the drive strength for heavy load conditions without risk of internal shoot-through.

The input side is isolated from the two output drivers by a 3.0-kV$_{RMS}$ isolation barrier, with a minimum of 100-V/ns common-mode transient immunity (CMTI).

Resistor programmable dead time gives the capability to adjust dead time for system constraints to improve efficiency and prevent output overlap. Other protection features include: Disable feature to shut down both outputs simultaneously when DIS is set high, integrated deglitch filter that rejects input transients shorter than 5-ns, and negative voltage handling for up to -2-V spikes for 200-ns on input and output pins. All supplies have UVLO protection.

Device Information(1)

PART NUMBER	PACKAGE	BODY SIZE (NOM)
UCC21222	SOIC (16)	9.9 mm × 3.91 mm

(1) For all available packages, see the orderable addendum at the end of the data sheet.

Functional Block Diagram

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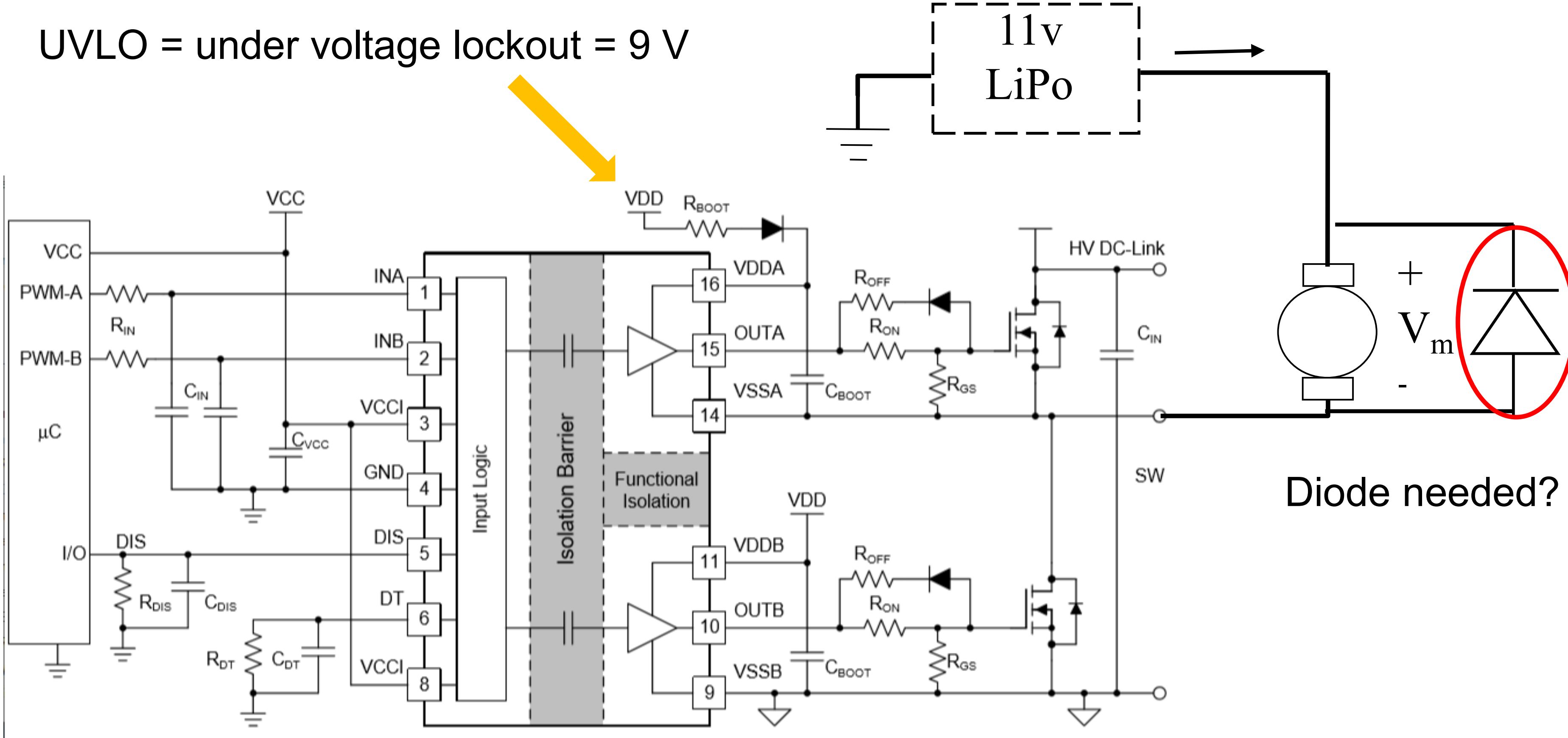
Low Side Drive example

UVLO = under voltage lockout = 9 V



Diode needed?

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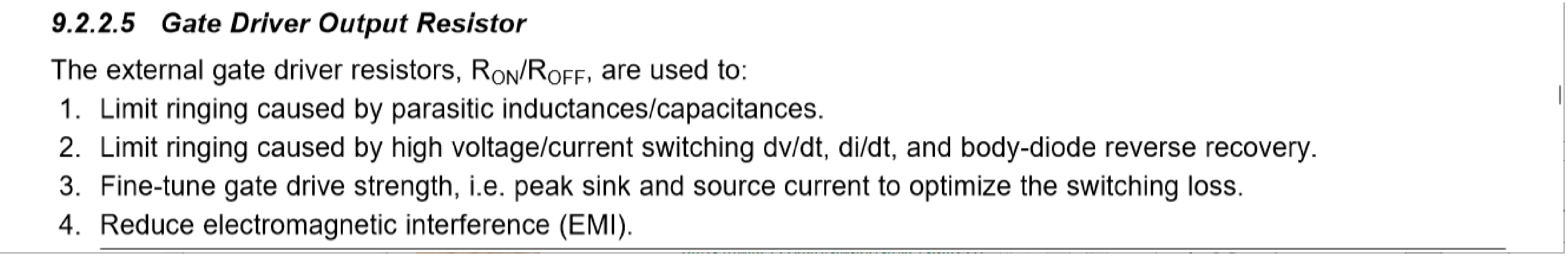
Figure 38. Typical Application Schematic

UCC 21222 design details



9.2.2.5 Gate Driver Output Resistor

The external gate driver resistors, R_{ON}/R_{OFF}, are used to:

1. Limit ringing caused by parasitic inductances/capacitances.
2. Limit ringing caused by high voltage/current switching dv/dt, di/dt, and body-diode reverse recovery.
3. Fine-tune gate drive strength, i.e. peak sink and source current to optimize the switching loss.
4. Reduce electromagnetic interference (EMI).

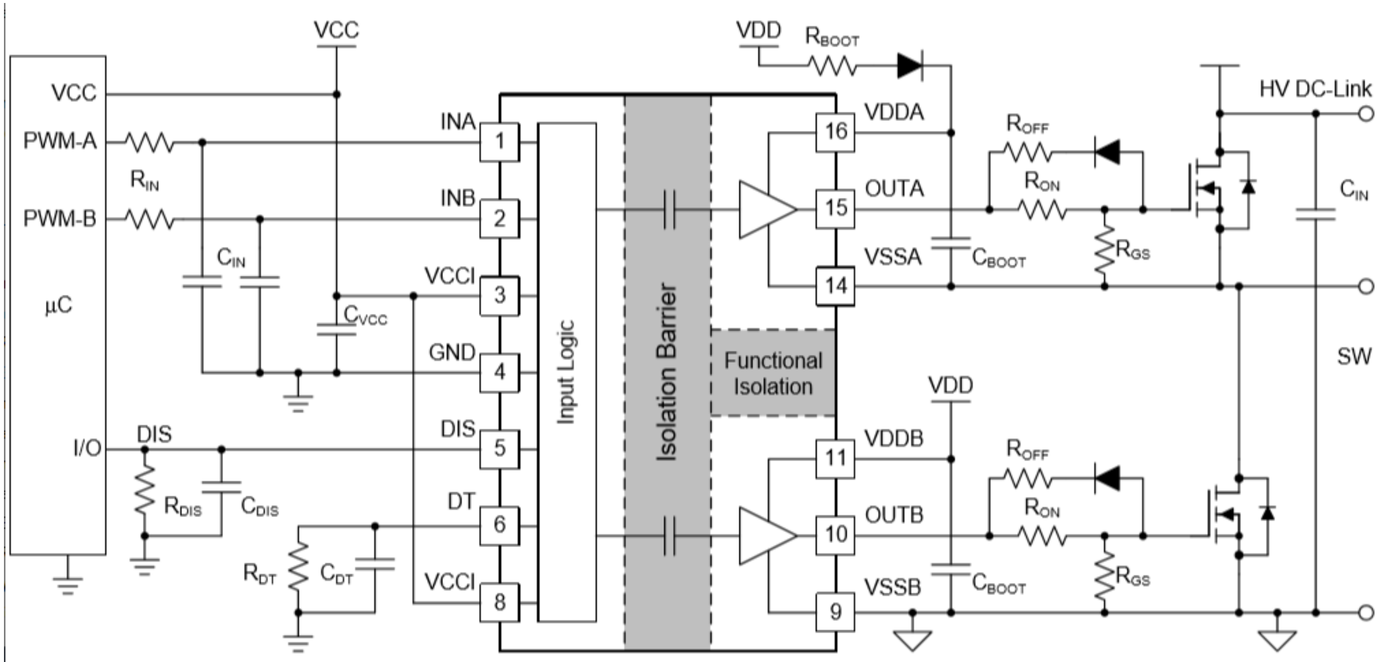


Figure 38. Typical Application Schematic

UCC 21222 internal details

UVLO: under voltage lockout (check data sheet)
DT: dead time useful for H Bridge

nctional Block Diagram

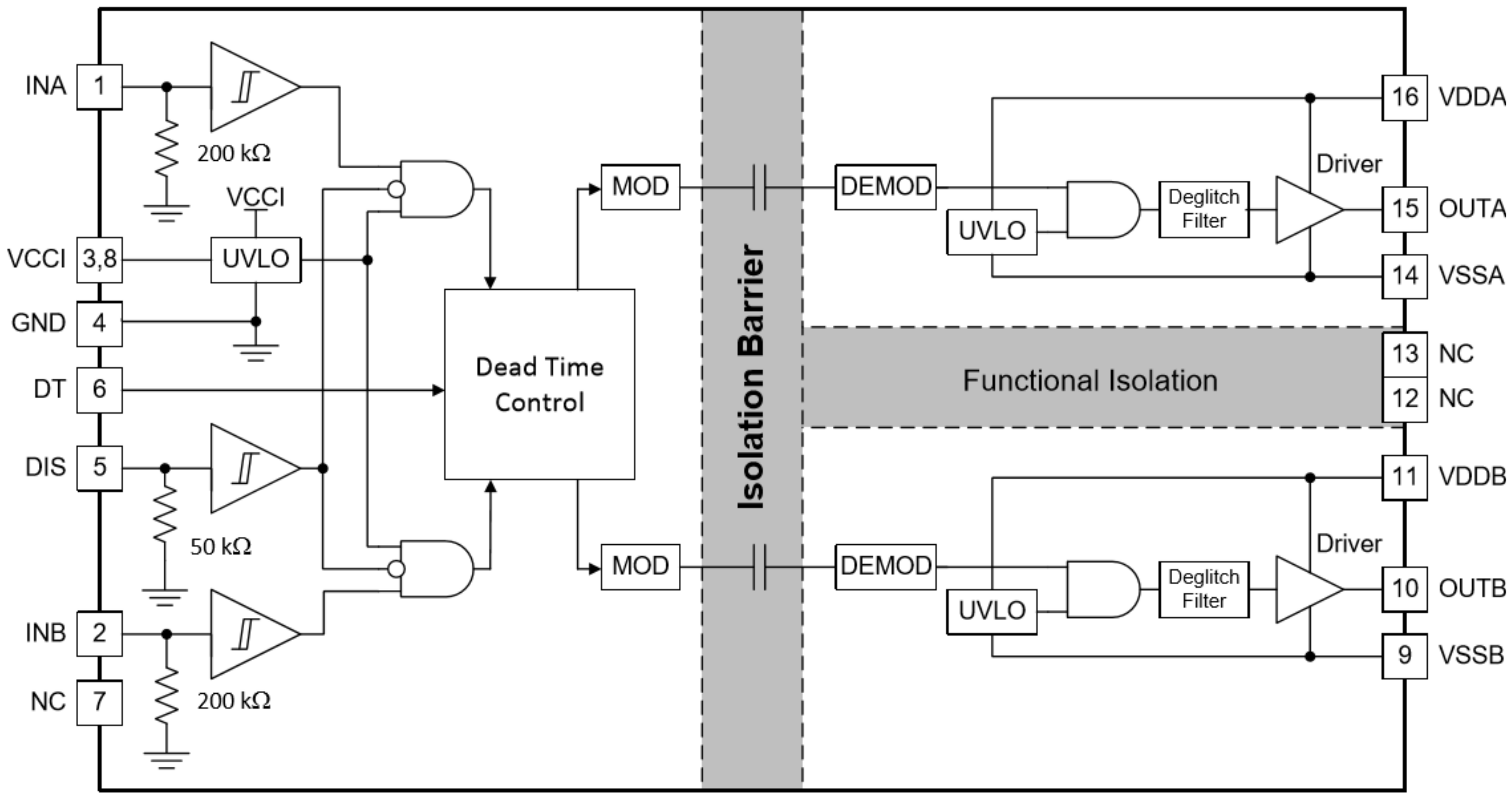
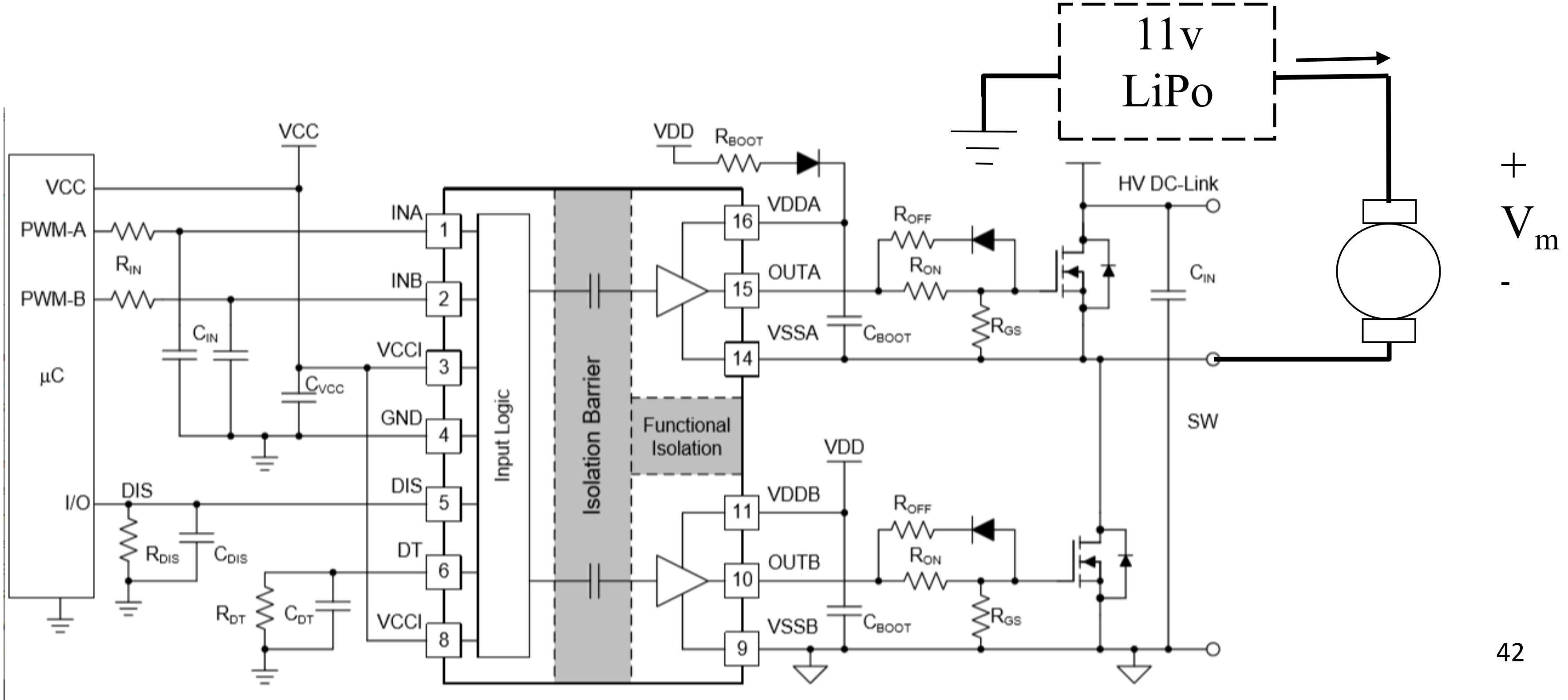


Table 3. INPUT/OUTPUT Logic Table[1]

INPUTS		DIS	OUTPUTS		NOTE
INA	INB		OUTA	OUTB	
L	L	L or Left Open	L	L	If the dead time function is used, output transitions occur after the dead time expires. See Programmable Dead Time (DT) Pin.
L	H	L or Left Open	L	H	
H	L	L or Left Open	H	L	
H	H	L or Left Open	L	L	DT is programmed with R_{DT}.
H	H	L or Left Open	H	H	DT pin is left open or pulled to VCCI.
Left Open	Left Open	L or Left Open	L	L	
X	X	H	L	L	

(1) "X" means L, H or left open. For improved noise immunity, TI recommends connecting INA, INB, and DIS to GND, and DT to VCCI, when these pins are not used.



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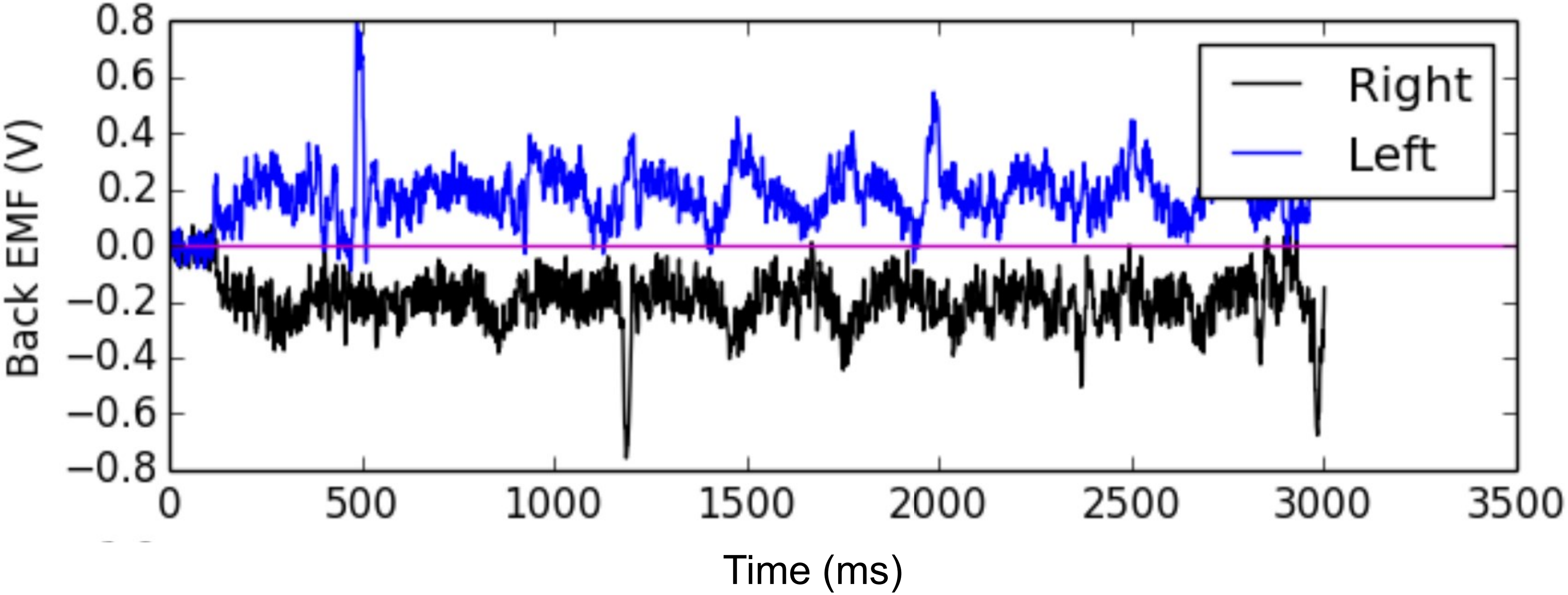
Digital Filtering

- Moving average
  - $y1[n] = (y[n-2]+y[n-1]+y[n])/3$
- Median filter (outlier rejection)
- Notch filter (mechanical vibration)
  - $y[n] = (x[n-2]+2x[n-1]+x[n])/4$

- Model based filtering (or Kalman filter)

Moving Average vs. Median Filter

Example: motor brush noise, back EMF measurement



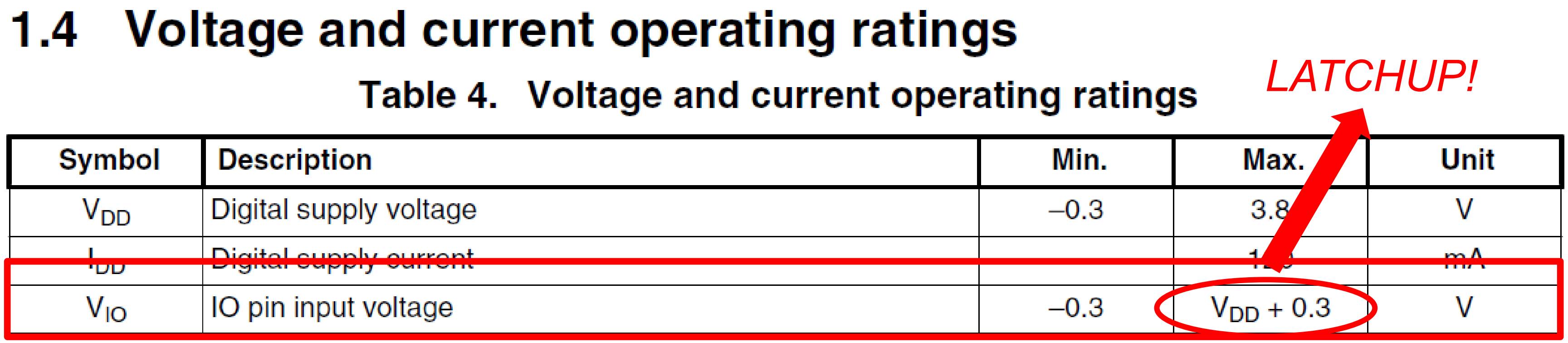
{0,2,-1,4,0,2,1,1,20,1,0,2} ➔

{0,2,-1,2,0,1,1,1,1,1} 3 element median filter

{0,2, 0.3,1.7, 2, 1,1.3, 7.3, 7.3, 7,1…} 3 elem MA

Latchup

- Make sure Huzzah32 powered first,
  before ESC,
  before position encoder



1.4 Voltage and current operating ratings

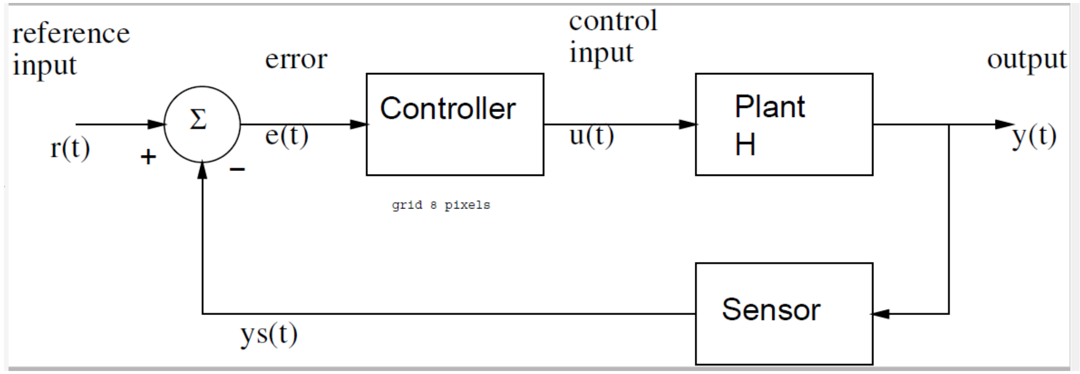
Table 4. Voltage and current operating ratings

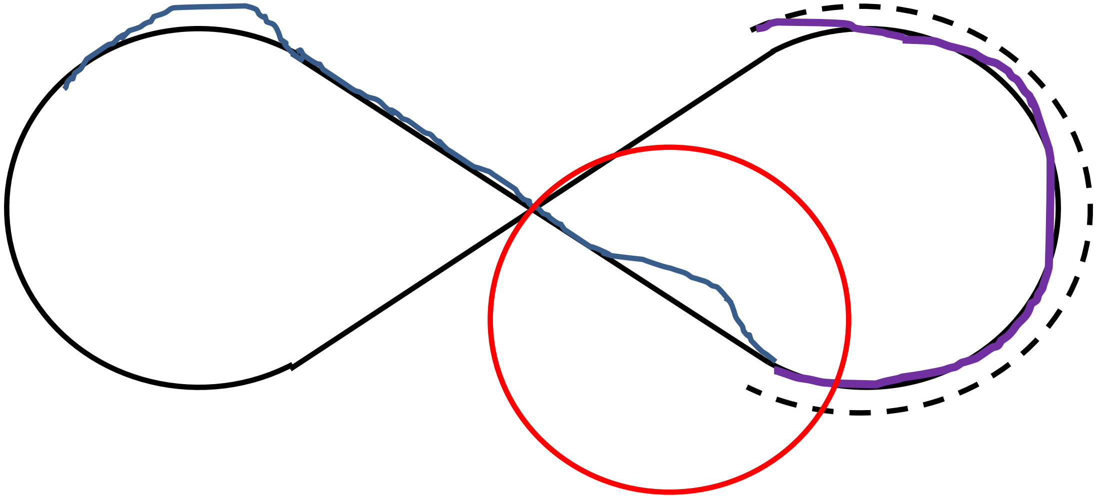
LATCHUP!

Symbol	Description	Min.	Max.	Unit
V_{DD}	Digital supply voltage	–0.3	3.8	V
I_{DD}	Digital supply current		1[illegible]	mA
V_{IO}	IO pin input voltage	–0.3	V_{DD} + 0.3	V

Caution: input voltage from sensor may be greater than 0.3V when CPU is off VDD = 0!

Proportional + Integral

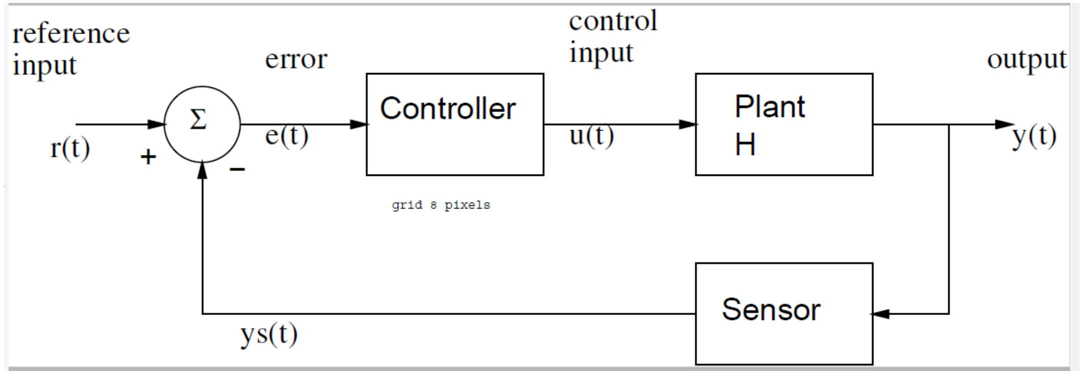


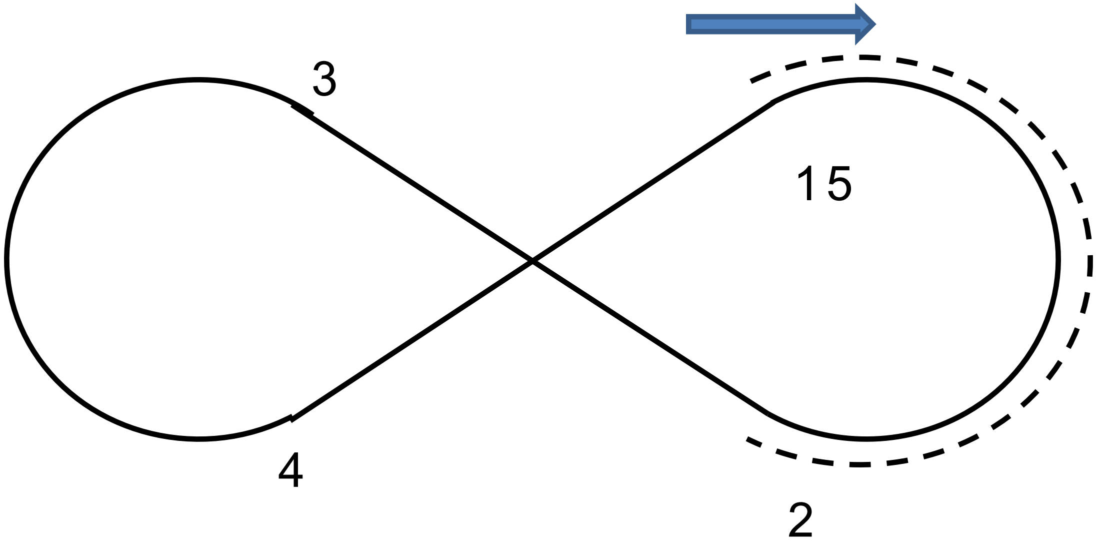


P+I control: delta =kp e + ki (integral e)
P control: delta = kp e

On board Anti-windup

Feedforward





r(x) =

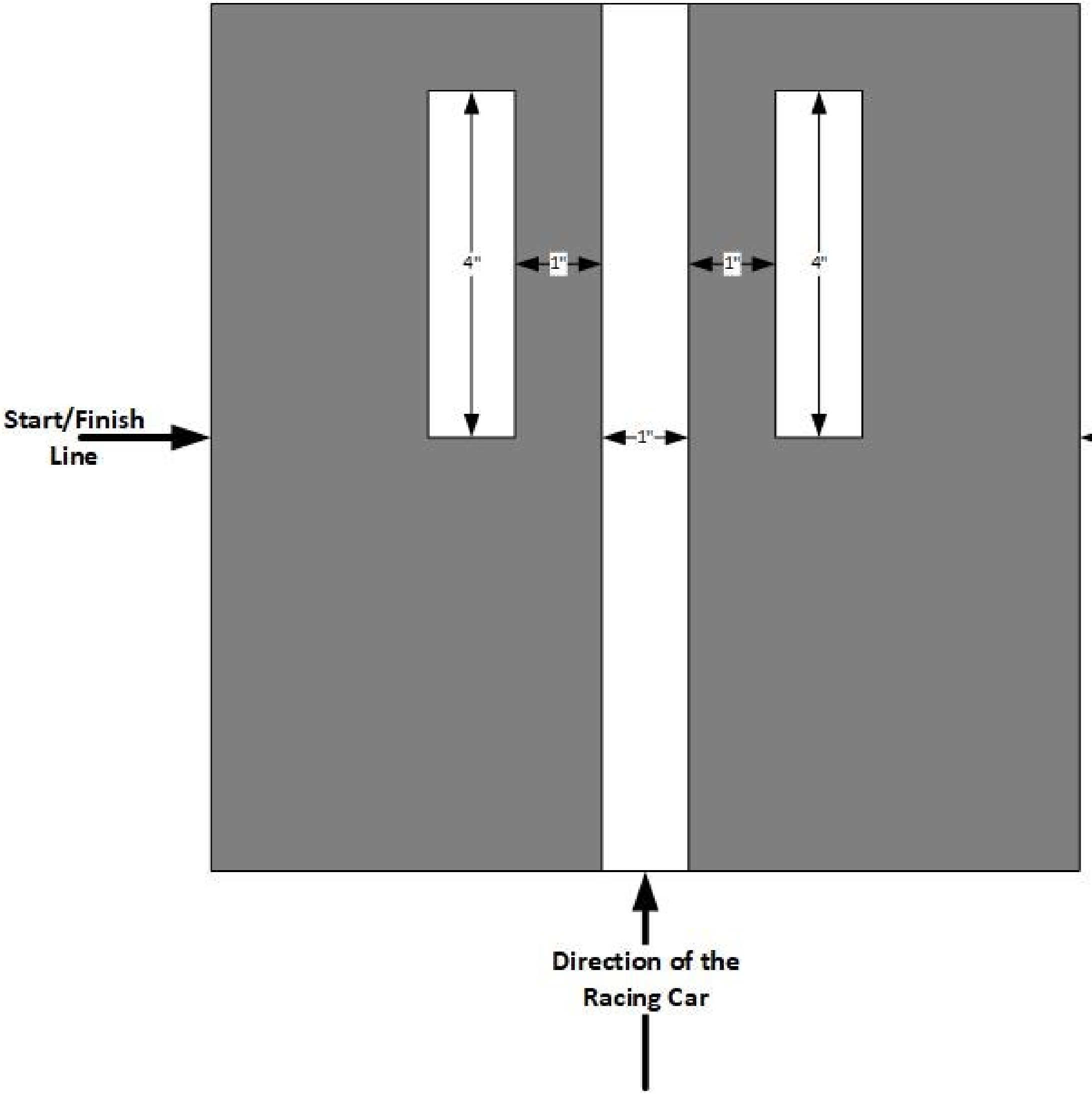
On board

NATCAR Notes

Cones +2 second
Finish line:The start/finish line will be marked with two 4-inch-long segments of 1-inch-wide white tape that are parallel to the track with 1-inch spacing, as shown in the figure below.

The car must automatically stop within 6 feet of the finish line after finishing the race.

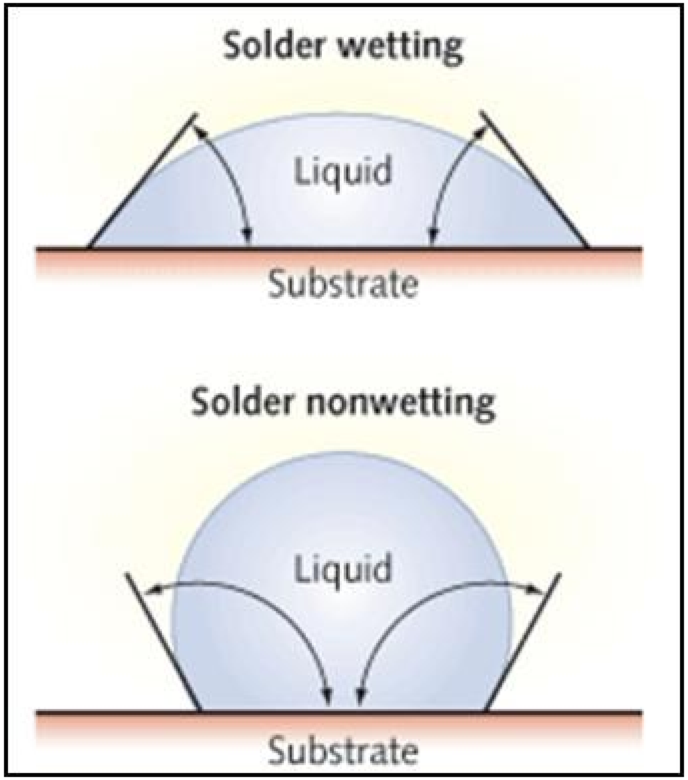
A penalty of 4 seconds will be added to the lap time for any car that does not automatically stop within the required region.



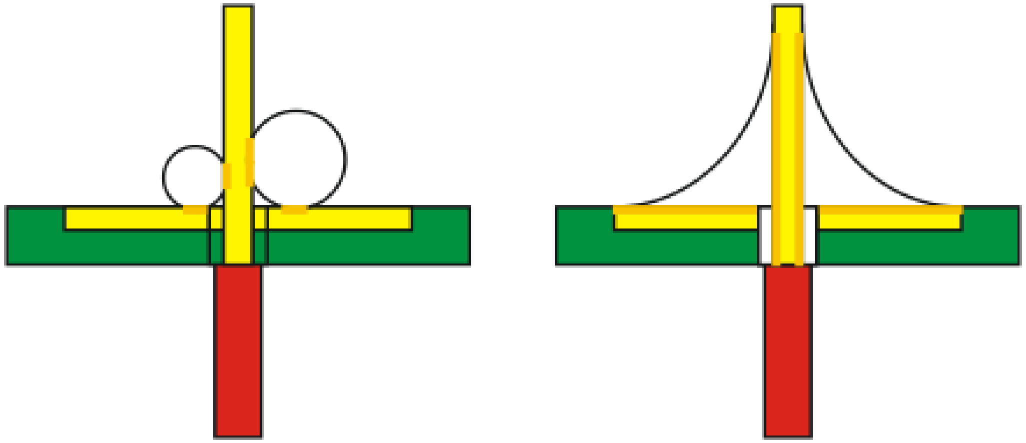
Electronic Interconnect and Components

EE192- Soldering Notes

- Oxide has lower energy than clean metal
- Higher energy surfaces attract molten solder
- Oxides have higher melting points than metals
- Oxides have lower thermal conductivity than metals
- Flux helps to prevent oxide formation, but is an insulator



From: http://solutions.palomartechnologies.com/Portals/60069/images//Wetting%20vs%20non-wetting%20conditions-resized-600.JPG



From:http://www.slagcoin.com/joystick/pcb_wiring/bond.png

NATCAR Notes

Cones +2 second
Finish line:The start/finish line will be marked with two 4-inch-long segments of 1-inch-wide white tape that are parallel to the track with 1-inch spacing, as shown in the figure below.

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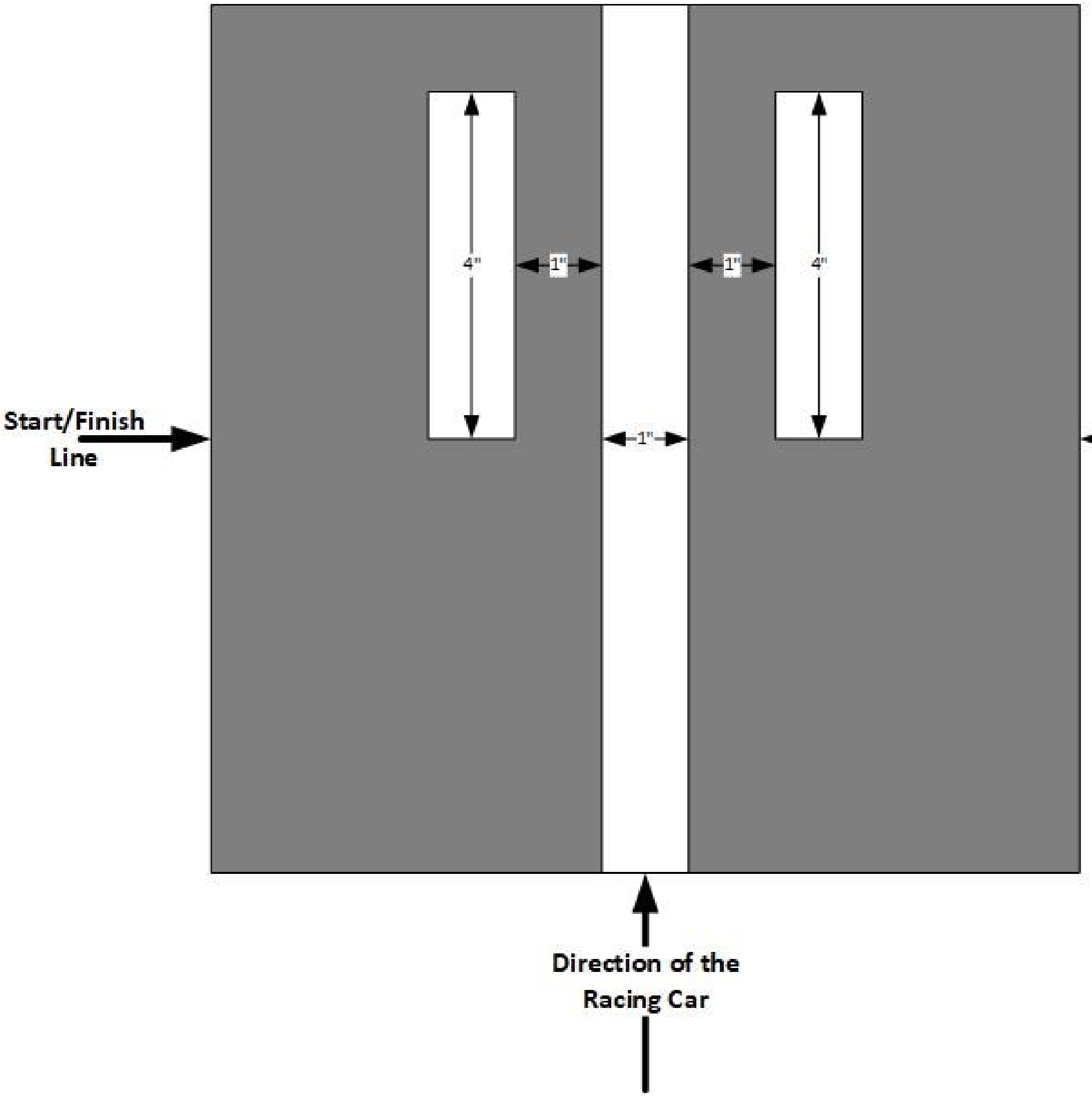


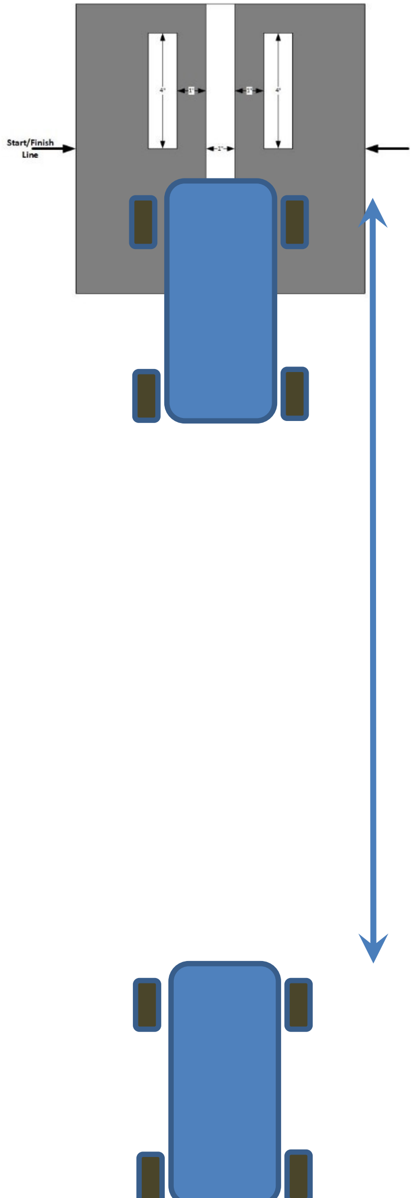
NATCAR Notes

1. Car can start in region shown (running start or avoid seeing stop line…) up to ``several feet” behind start/stop line

2. A running car can continue running for consecutive laps. If car is doing multiple laps without stopping, 4 second penalty is applied to intermediate laps.

The car must automatically stop within 6 feet of the finish line after finishing the race.

A penalty of 4 seconds will be added to the lap time for any car that does not automatically stop within the required region.



Permitted
Start region