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
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.
Topics

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Robust Wiring


Flex vs stranded
Topics

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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.
$8V = 40A$

$0.25$

$+3 \ i_m \ \text{amps}$

$8V = k \ \Theta_m$

$0.25$

$40A = 5 \ \Theta_m$

$t (\text{sec})$

$8e^{-1} = 29V$

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

$V_m = k \ e^\Theta_m$

$t > 0.25$:

$t_m = k \ e^\Theta_m$

$\text{velocity m/s}$

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

$\dot{\theta}_m(2) = 4 \ \text{m/s}$.
EECS192 Lecture 9
Motor Drive Introduction
Mar. 16, 2021

Topics
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• Control Fundamentals
V-rep simulation- HW2

demo
Topics
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• Robust wiring
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• Motor Drive- details
• Control Fundamentals
Progress Report Due Fri 4/9

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

Back EMF
Motor electromechanical behavior

Also- see motor worksheet......

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

Conclusion:
\(<i_m>=?\)

Conclusion:
\(<i_m>=?\)
Given: $R_m = 0.1$ ohms, $V_{batt} = 7.2$ V, $R_{bat} = 0$.  
$V_{ds} = ? \Rightarrow I_{ds} = ?$ amps 

Driving MOSFETs and motor

MOSFETs and motor drive

(LiPo 11 V!)

$G = \text{gate}$
$D = \text{Drain}$
$S = \text{Source}$

$V_{DS} = 3.6$ V, $I_{DS} = ?$

Load line
Driving MOSFETs and motor

R_m = 0.1 ohms, V_{batt} = 7.2 V, R_{bat} = 0.
V_{ds} = 3.6 V \Rightarrow I_{ds} = (7.2 - 3.6 V)/(0.1 \text{ ohm}) = 36 \text{ amps}

V_{gs} = 20 V
P_{trans} \sim 35 W

V_{gs} = 6 V
P_{trans} \sim 72 W

Key design points:
1) High $V_{gs}$ better than low $V_{gs}$
2) Switch quickly
3) Make sure $V_s = 0$ (big ground)
Consider the NMOS motor drive shown below:

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) 90%

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

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Motor Drive with UCC21222 gate driver

Details On board…. 

Checklist: 
1) Emergency stop 
2) Reset Protection 
3) Snubbing
Driving MOSFETs and motor

How to choose PWM frequency: UCC21222 driver constraint

\[ I = C \frac{dv}{dt} \]

(on board)

Gate capacitance 5000 pF

---

6.10 Switching Characteristics

\( V_{\text{CC1}} = 3.3 \text{ V or 5.5 V}, 0.1-\mu\text{F capacitor from VCC1 to GND, } V_{\text{VDDA}} = V_{\text{VDDB}} = 12 \text{ V, 1-\mu\text{F capacitor from VDDA and VDDB to VSSA and VSSB, load capacitance } C_{\text{OUT}} = 0 \text{ pF, } T_A = -40^\circ \text{C to } +125^\circ \text{C unless otherwise noted}^{(1)}. \)

<table>
<thead>
<tr>
<th>PARAMETER</th>
<th>TEST CONDITIONS</th>
<th>MIN</th>
<th>TYP</th>
<th>MAX</th>
<th>UNIT</th>
</tr>
</thead>
</table>
| \( t_{\text{RISE}} \) | Output rise time, see Figure 28  
\( C_{\text{VDD}} = 10 \mu\text{F, } C_{\text{OUT}} = 1.8 \text{ nF, } V_{\text{VDDA, VDDB}} = 12 \text{ V, } f = 1 \text{ kHz} \) | 5   | 16  |     | ns   |
| \( t_{\text{FALL}} \) | Output fall time, see Figure 28  
\( C_{\text{VDD}} = 10 \mu\text{F, } C_{\text{OUT}} = 1.8 \text{ nF, } V_{\text{VDDA, VDDB}} = 12 \text{ V, } f = 1 \text{ kHz} \) | 6   | 12  |     | ns   |

**OUTPUT**

\( I_{\text{OA+}, I_{\text{OB+}}} \) Peak output source current  
\( C_{\text{VDD}} = 10 \mu\text{F, } C_{\text{LOAD}} = 0.18 \mu\text{F, } f = 1 \text{ kHz, bench measurement} \)  
4  
A

\( I_{\text{OA-}, I_{\text{OB-}}} \) Peak output sink current  
\( C_{\text{VDD}} = 10 \mu\text{F, } C_{\text{LOAD}} = 0.18 \mu\text{F, } f = 1 \text{ kHz, bench measurement} \)  
6  
A
Driving MOSFETs and motor

CSD18542KTT Power MOSFET

How to choose PWM frequency?

<table>
<thead>
<tr>
<th>DYNAMIC CHARACTERISTICS</th>
<th>3900</th>
<th>5070</th>
<th>pF</th>
</tr>
</thead>
<tbody>
<tr>
<td>$C_{iss}$ Input capacitance</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$C_{oss}$ Output capacitance</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$C_{rss}$ Reverse transfer capacitance</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$R_{G}$ Series gate resistance</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$Q_{g}$ Gate charge total (4.5 V)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$Q_{g}$ Gate charge total (10 V)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$Q_{gd}$ Gate charge gate-to-drain</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$Q_{gs}$ Gate charge gate-to-source</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$Q_{g(th)}$ Gate charge at $V_{th}$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$Q_{oss}$ Output charge</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$t_{d(on)}$ Turnon delay time</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$t_{f}$ Rise time</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$t_{d(off)}$ Turnoff delay time</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$t_{f}$ Fall time</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Cdode CHARACTERISTICS</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>$V_{SD}$ Diode forward voltage</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$Q_{rr}$ Reverse recovery charge</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$t_{rr}$ Reverse recovery time</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

$@10V, C=Q/V=57nC/10V = 5.7 \text{ nF}$
Low side motor drive

- $V_{m}$
- $V_{DS}$
- $+ V_{BAT}$
- $V_{GS}$
- MOSFET body diode

What about motor inductance?

- $0.1$ ohm
- $L$
- $i_m$
- $R_m$
- $V_L$
- $2v$
- Snubber/flyback diode
- $V_{DS}$
Assume ideal diode, 17 kHz ideal switch, L = 100 \mu H. Time constant \( \tau = 1 \text{ ms} \).

Steady state, constant velocity.

Initial rate: \( V/L = +8 \times 10^4 \text{ amp/sec} \)

\[-10 - 2 \text{ V} - (1.6 \text{ A})(0.1 \text{ ohm}) = -13.6 \text{ V} \]
Assume ideal diode, ideal switch, L = 100 μH. Time constant \( \tau = 1 \) ms. Steady state, constant velocity. Assume \( i_{\text{min}} = 5 \) amp.

Motor+flywheel diode

Note: 25 kHz PWM reduces peak current
\[ V_{DS} = 10V - V_{\text{DIODE}} \]
H Bridge Concept

<table>
<thead>
<tr>
<th>S1</th>
<th>S2</th>
<th>S3</th>
<th>Function?</th>
</tr>
</thead>
<tbody>
<tr>
<td>Off</td>
<td>Off</td>
<td>Off</td>
<td>Off</td>
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<tr>
<td>On</td>
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<td>Off</td>
<td>On</td>
</tr>
<tr>
<td>Off</td>
<td>On</td>
<td>On</td>
<td>Off</td>
</tr>
<tr>
<td>On</td>
<td>On</td>
<td>Off</td>
<td>Off</td>
</tr>
<tr>
<td>On</td>
<td>Off</td>
<td>On</td>
<td>Off</td>
</tr>
<tr>
<td>Off</td>
<td>On</td>
<td>Off</td>
<td>on</td>
</tr>
</tbody>
</table>
Need protection logic!

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

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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:

\[ \dot{x} = a x + b k_p e(t) = a x + b k_p (r - x) = (a - b k_p) x + b k_p r. \]

Zero Input Response (non-zero init condx):

\[ x(t) = x(0) e^{(a - b k_p)t} \quad \text{for} \quad t \geq 0. \]

a' = a - b k_p \quad b' = b k_p

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

\[ x(t_o) = e^{a' t_o} x(0) + \int_0^{t_o} e^{a' (t_o - \tau)} b' r(\tau) d\tau. \quad (10) \]

Step Response (zero init condx) by convolution:

\[ x(t_o) = b' \int_0^{t_o} e^{a' t_o - a' \tau} d\tau = \frac{-b' e^{a' t_o}}{a'} e^{-a' \tau} \bigg|_{0}^{t_o} = \frac{b'}{a'} (1 - e^{-a' t_o}). \quad (11) \]
Control Synopsis - Discrete Time

Superposition of Step Responses

\[ x((k + 1)T) = e^{a(k+1)T} x(0) + e^{a(k+1)T} \int_0^{(k+1)T} e^{-a\tau} b u(\tau) d\tau. \]  \hspace{1cm} (15)

\[ x(kT) = e^{akT} x(0) + e^{akT} \int_0^{kT} e^{-a\tau} b u(\tau) d\tau. \]  \hspace{1cm} (14)

\[ x((k+1)T) = e^{aT} x(kT) + e^{a(k+1)T} \int_{kT}^{(k+1)T} e^{-a\tau} b u(\tau) d\tau = e^{aT} x(kT) + \int_0^{T} e^{a\lambda} b u(kT) d\lambda, \]  \hspace{1cm} (16)
Control Synopsis- Discrete Time

\[ G(T) \equiv e^{aT} \quad \text{and} \quad H(T) \equiv b \int_{0}^{T} e^{a\lambda} d\lambda . \]  
(17)

State equations:

\[ x((k + 1)T) = G(T)x(kT) + H(T)u(kT) \]  
(18)

Output equations:

\[ y(kT) = Cx(kT) + Du(kT) . \]  
(19)

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

\[ x(k) = G^k x(0) + \sum_{j=0}^{k-1} G^{k-j-1} H u(j) . \]  
(23)
Control Synopsis - Discrete Time

Control Law (P):

\[ U(kT) = k_p [r(kT) - x(kT)] \]

New state equations:

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

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

For stability:

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

Notes: stability depends on gain \textbf{and} \( T \)!
Discrete Time Control

\[ u[k] = kp \cdot (r[k] - x[k]) \]

Let \( x[k] = y[k] \)

\[ e(t), \ u = kp \ e(t) \]
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 \( u[n]=3(r[n]-x[n]) = 3e[n] \),

<table>
<thead>
<tr>
<th>t (sec)</th>
<th>x(t)</th>
<th>e(t) = r(t) - x(t)</th>
<th>u(t)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0^-</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td>1</td>
<td>2</td>
<td>-1</td>
<td>-3</td>
</tr>
<tr>
<td>2</td>
<td>-1</td>
<td>2</td>
<td>6</td>
</tr>
<tr>
<td>3</td>
<td>3.5</td>
<td>-2.5</td>
<td>-7.5</td>
</tr>
<tr>
<td>4</td>
<td>-3.5</td>
<td>4.5</td>
<td>13.5</td>
</tr>
</tbody>
</table>

Watch out for delay!
Watch out for excess gain!
EECS192 Lecture 9
Motor Drive Introduction
Mar. 16, 2021

Topics

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• 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

UCC21222 4-A, 6-A, 3.0-kVRMS 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-Vpk
- Narrow Body SOIC-16 (D) Package
- Safety-Related Certifications (Planned):
  - 4242-VPK Isolation per DIN V VDE V 0884-11: 2017-01 and DIN EN 61010-1
  - 3000-Vrms 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-kVRMS 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)

<table>
<thead>
<tr>
<th>PART NUMBER</th>
<th>PACKAGE</th>
<th>BODY SIZE (NOM)</th>
</tr>
</thead>
<tbody>
<tr>
<td>UCC21222</td>
<td>SOIC (16)</td>
<td>9.9 mm x 3.91 mm</td>
</tr>
</tbody>
</table>

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

Functional Block Diagram
Low Side Drive example

UVLO = under voltage lockout = 9 V

Diode needed?
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

Functional Block Diagram
Table 3. INPUT/OUTPUT Logic Table

<table>
<thead>
<tr>
<th>INPUTS</th>
<th>DIS</th>
<th>OUTPUTS</th>
<th>NOTE</th>
</tr>
</thead>
<tbody>
<tr>
<td>INA</td>
<td>INB</td>
<td>OUTA</td>
<td>OUTB</td>
</tr>
<tr>
<td>L</td>
<td>L</td>
<td>L or Left Open</td>
<td>L</td>
</tr>
<tr>
<td>L</td>
<td>H</td>
<td>L or Left Open</td>
<td>L</td>
</tr>
<tr>
<td>H</td>
<td>L</td>
<td>L or Left Open</td>
<td>H</td>
</tr>
<tr>
<td>H</td>
<td>H</td>
<td>L or Left Open</td>
<td>L</td>
</tr>
<tr>
<td>Left Open</td>
<td>Left Open</td>
<td>L or Left Open</td>
<td>H</td>
</tr>
<tr>
<td>X</td>
<td>X</td>
<td>H</td>
<td>L</td>
</tr>
</tbody>
</table>

(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.
Digital Filtering

• Moving average
  – $y_1[n] = (y[n-2]+y[n-1]+y[n])/3$

• 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\} \rightarrow
\{0, 2, -1, 2, 0, 1, 1, 1, 1, 1\} \text{ 3 element median filter}
\{0, 2, 0.3, 1.7, 2, 1, 1.3, 7.3, 7.3, 7, 1\ldots\} \text{ 3 elem MA}
Latchup

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

1.4 Voltage and current operating ratings

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Min.</th>
<th>Max.</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V_{DD}$</td>
<td>Digital supply voltage</td>
<td>-0.3</td>
<td>3.8</td>
<td>V</td>
</tr>
<tr>
<td>$I_{DD}$</td>
<td>Digital supply current</td>
<td>1.0</td>
<td></td>
<td>mA</td>
</tr>
<tr>
<td>$V_{IO}$</td>
<td>IO pin input voltage</td>
<td>-0.3</td>
<td>$V_{DD} + 0.3$</td>
<td>V</td>
</tr>
</tbody>
</table>

Caution: input voltage from sensor may be greater than 0.3V when CPU is off $V_{DD} = 0$!
Proportional + Integral

P+I control: \( \delta = kp \ e + ki \ (\text{integral } e) \)

P control: \( \delta = kp \ e \)

On board  Anti-windup
Feedforward

\[ r(x) = \begin{cases} 2 \\ 3 \\ 4 \end{cases} \]
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.palomartechologies.com/Portals/600
69/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.

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.
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.