EECS192 Lecture 3
Feb. 4, 2020

Notes:
• Handouts: lab rules
• 2/11 project proposal – upload to bcourses by Tues 330 pm
• CP 2: 2/7: bench top Motor drive/stall, steering servo
• Quiz 1: motor behavior Tues 2/11 (See Motor Worksheet week 2)
• CalDay Sat April 4/18

Topics
• Timing in Linux:
• Motor electrical model
  – Motor electromechanical behavior
• Driving MOSFETs and motor
  – UCC21222 MOSFET driver
• PWM issues for motor
• H Bridge motor drive
• (Back EMF measurement)
• Buck Converter (on Handout board)
CheckPoint 2- highlights. See Piazza for full spec

C2.1: Power from bench supply set to 12v.

C2.2: Both LEDs for both buck converters should light up
   C2.2.1: The 5v buck converter output between 4.75 and 5.25v
   C2.2.2: The 6v buck converter output 5.7 and 6.3v

C2.3: With all wheels off the ground, the motor should spin forward (from keybd command)

C2.4: With a non-super (ie, not a Savox) servo connected, demonstrate turning between left, center, and right positions (from keybd command)

C2.6: Motor stall test: 30% duty cycle for 5 seconds, with the wheels held in place.

**PWM Frequency > 10 kHZ (Why??)**

#define RC_MOTOR_DEFAULT_PWM_FREQ 25000

C2.6.2: The current limit on the power supply must be at least 20A Use the higher current connectors on your power supplies. **Do not use test leads for motor current.**
C2.6.5: No component should get too hot to touch

C2.9: All members must fill out the checkpoint survey before the checkoff close. Completion is individually graded.
Delay timing using rc library

```
start_time = rc_nanos_thread_time();
// routine to be timed:
    for(j = 0; j< 1000; j++)
        {shared_mem_32bit_ptr[ENCODER_MEM_OFFSET+1] = 1;
        // set flag to start conversion by PRU
        while(shared_mem_32bit_ptr[ENCODER_MEM_OFFSET+1] == 1);
        // wait for PRU to zero word
        for(i = 0; i< 128; i++)
            {linescan[i]=
                (int) shared_mem_32bit_ptr[ENCODER_MEM_OFFSET+2+i];
            // copy data
            }
        }
end_time = rc_nanos_thread_time();
run_time = end_time - start_time;
```
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DC Motor Physical Model

\[
F = i l \times B \\
\tau = r_1 \times F_1 + r_2 \times F_2
\]
Motor Electrical Model
(neglect inductor)

Motor model
Back EMF
Motor electromechanical behavior

Continued on board
Also- see motor worksheet......

Note: missing e-stop!
For this problem, consider a DC permanent magnet motor (as used in your car). The car is on a carpet and moves in a straight line with no slip between the wheels and the carpet. The car is initially moving at a speed of 2 meters per second.

You can assume a motor model as shown below. The qualitative shape of the curves is more important than magnitudes.

Let peak speed = 5 m/sec
Accel = 5 m/s²
k_e = 1 v/(m/sec)

(For answer see sp99 final solution)
PWM for Main Motor control

\[ <i_m> = \left( \frac{T}{T_0} \right) i_{\text{max}} \]

Is \( i_{\text{max}} \) constant?
Motor Electrical Model

Back EMF
Motor electromechanical behavior

Also- see motor worksheet……

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

Conclusion:
\[ <i_m> = ? \]
Given: $R_m = 0.1$ ohms, $V_{batt} = 7.2$ V, $R_{bat} = 0$.

$V_{ds} = ? \Rightarrow I_{ds} = ?$ amps

(LiPo 11 V!)
Driving MOSFETs and motor

Rm = 0.1 ohms, Vbatt = 7.2 V, Rbat = 0.
Vds = 3.6V \Rightarrow I_{ds} = (7.2-3.6V)/(0.1 \text{ ohm}) = 36 \text{ amps}

Vgs = 20V
P_{trans} \sim 35 \text{ W}

Vgs = 6V
P_{trans} \sim 72 \text{ W}

Key design points:
1) High Vgs better than low Vgs
2) Switch quickly
3) Make sure Vs=0 (big ground)
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Driving MOSFETs and motor

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)

<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
Motor Drive with UCC21222 gate driver

Details On board….

Checklist:
1) Emergency stop
2) Reset Protection
3) Snubbing
### How to choose PWM frequency?

#### Dynamic Characteristics

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Description</th>
<th>Units</th>
<th>Value 1</th>
<th>Value 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Input capacitance</td>
<td>$C_{iss}$</td>
<td>$V_{GS} = 0$ V, $V_{DS} = 30$ V, $f = 1$ MHz</td>
<td>pF</td>
<td>3900</td>
<td>5070</td>
</tr>
<tr>
<td>Output capacitance</td>
<td>$C_{oss}$</td>
<td>$V_{DS} = 30$ V, $I_D = 100$ A</td>
<td>pF</td>
<td>570</td>
<td>740</td>
</tr>
<tr>
<td>Reverse transfer capacitance</td>
<td>$C_{rss}$</td>
<td>$V_{GS} = 0$ V, $V_{DS} = 30$ V</td>
<td>pF</td>
<td>11</td>
<td>14</td>
</tr>
<tr>
<td>Series gate resistance</td>
<td>$R_G$</td>
<td>$V_{DS} = 30$ V, $I_D = 100$ A</td>
<td>$\Omega$</td>
<td>1.3</td>
<td>2.6</td>
</tr>
<tr>
<td>Gate charge total (4.5 V)</td>
<td>$Q_g$</td>
<td>$V_{DS} = 30$ V, $V_{GS} = 0$ V</td>
<td>nC</td>
<td>21</td>
<td>27</td>
</tr>
<tr>
<td>Gate charge total (10 V)</td>
<td>$Q_g$</td>
<td>$V_{DS} = 30$ V, $V_{GS} = 0$ V</td>
<td>nC</td>
<td>44</td>
<td>57</td>
</tr>
<tr>
<td>Gate charge gate-to-drain</td>
<td>$Q_{gd}$</td>
<td>$V_{DS} = 30$ V, $V_{GS} = 0$ V</td>
<td>nC</td>
<td>6.9</td>
<td></td>
</tr>
<tr>
<td>Gate charge gate-to-source</td>
<td>$Q_{gs}$</td>
<td>$V_{DS} = 30$ V, $V_{GS} = 0$ V</td>
<td>nC</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td>Gate charge at $V_{th}$</td>
<td>$Q_{g(\text{th})}$</td>
<td>$V_{DS} = 30$ V, $V_{GS} = 0$ V</td>
<td>nC</td>
<td>7.3</td>
<td></td>
</tr>
<tr>
<td>Output charge</td>
<td>$Q_{oss}$</td>
<td>$V_{DS} = 30$ V, $I_D = 100$ A</td>
<td>nC</td>
<td>63</td>
<td></td>
</tr>
<tr>
<td>Turnon delay time</td>
<td>$t_{d(\text{on})}$</td>
<td>$V_{DS} = 30$ V, $I_D = 100$ A</td>
<td>ns</td>
<td>6</td>
<td></td>
</tr>
<tr>
<td>Rise time</td>
<td>$t_r$</td>
<td>$V_{DS} = 30$ V, $I_D = 100$ A</td>
<td>ns</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td>Turnoff delay time</td>
<td>$t_{d(\text{off})}$</td>
<td>$V_{DS} = 30$ V, $I_D = 100$ A</td>
<td>ns</td>
<td>18</td>
<td></td>
</tr>
<tr>
<td>Fall time</td>
<td>$t_f$</td>
<td>$V_{DS} = 30$ V, $I_D = 100$ A</td>
<td>ns</td>
<td>21</td>
<td></td>
</tr>
</tbody>
</table>

#### Diode Characteristics

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Description</th>
<th>Units</th>
<th>Value</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diode forward voltage</td>
<td>$V_{SD}$</td>
<td>$I_{SD} = 100$ A, $V_{GS} = 0$ V</td>
<td>V</td>
<td>0.9</td>
<td>1.0</td>
</tr>
<tr>
<td>Reverse recovery charge</td>
<td>$Q_{rr}$</td>
<td>$V_{DS} = 30$ V, $I_F = 100$ A, di/dt = 300 A/\mu s</td>
<td>nC</td>
<td>148</td>
<td></td>
</tr>
<tr>
<td>Reverse recovery time</td>
<td>$t_{rr}$</td>
<td>$V_{DS} = 30$ V, $I_F = 100$ A, di/dt = 300 A/\mu s</td>
<td>ns</td>
<td>53</td>
<td></td>
</tr>
</tbody>
</table>

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Driving MOSFETs and motor

CSD18542KTT Power MOSFET
Driving MOSFETs and motor

How to choose PWM frequency: UCC21222 driver constraint

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

Gate capacitance 5000 pF
(on board)

6.10 Switching Characteristics

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

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

**OUTPUT**

| \( I_{OA+}, I_{OB+} \) | Peak output source current | \( C_{VDD} = 10 \mu\text{F, } C_{LOAD} = 0.18 \mu\text{F, } f = 1 \text{ kHz, bench measurement} \) | 4   |     | A   |
| \( I_{OA-}, I_{OB-} \) | Peak output sink current | \( C_{VDD} = 10 \mu\text{F, } C_{LOAD} = 0.18 \mu\text{F, } f = 1 \text{ kHz, bench measurement} \) | 6   |     | A   |
Low Side Drive example

UVLO = under voltage lockout = 9 V

11v LiPo

Diode needed?

Figure 38. Typical Application Schematic
Table 3. INPUT/OUTPUT Logic Table\(^{(1)}\)

<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>H</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.

\[
11v \quad \text{LiPo} \quad + \quad V_m \quad -
\]
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
UVLO: under voltage lockout (check data sheet)
DT: dead time useful for H Bridge
Topics

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- Driving MOSFETs and motor
  - UCC21222 MOSFET driver
- PWM issues for motor (inductance)
- H Bridge motor drive
- (Back EMF measurement)
- Buck Converter (on Handout board)
What does high side transistor do?
Assume ideal diode, ideal switch, \( L = 100 \, \mu\text{H} \). Time constant \( \tau = 1 \, \text{ms} \).

Steady state, constant velocity.

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

Diode reverse breakdown voltage
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
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H Bridge Concept

<table>
<thead>
<tr>
<th>S1</th>
<th>S2</th>
<th>S3</th>
<th>S4</th>
<th>Function?</th>
</tr>
</thead>
<tbody>
<tr>
<td>Off</td>
<td>Off</td>
<td>Off</td>
<td>Off</td>
<td></td>
</tr>
<tr>
<td>On</td>
<td>Off</td>
<td>Off</td>
<td>On</td>
<td></td>
</tr>
<tr>
<td>Off</td>
<td>On</td>
<td>On</td>
<td>Off</td>
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<tr>
<td>On</td>
<td>On</td>
<td>Off</td>
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<td>On</td>
<td>Off</td>
<td>On</td>
<td>Off</td>
<td></td>
</tr>
<tr>
<td>Off</td>
<td>On</td>
<td>Off</td>
<td>On</td>
<td></td>
</tr>
</tbody>
</table>
Need protection logic!

H bridge

11v LiPo

!!!CAUTION!!!
Software fries hardware....
Need protection logic-74HCxxx
Estop?
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Differential amp to read back EMF for H Bridge driving motor. Change values for 12V Back EMF…
\[ V_{DS} = 10V - V_{DIODE} \]

**Back EMF velocity sensing**
Topics

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Buck Converter - DC-DC

Why? Efficiency ~90%

Waveforms on board (also see buck converter notes.)
Buck: high to low. Boost: low-to-high
Buck Converter

https://en.wikipedia.org/wiki/Buck_converter
Buck Voltage Convertor

ON

OFF
LMR33630 Buck Converter
... multiple capacitors can be used in parallel to bring the minimum effective capacitance up to the required value. This can also ease the RMS current requirements on a single capacitor.
Figure 14. Typical PWM Switching Waveforms
$V_{IN} = 12\, V$, $V_{OUT} = 5\, V$, $I_{OUT} = 3\, A$, $f_S = 400\, kHz$
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
Summary

- Wiring to prevent high Vgs
- Wiring to prevent high current through low power devices
- Linear regulator
- Buck converter