# EECS192 Lecture 7
Mar. 3, 2020

**Notes**:

1. 2. Community Spirit: PCB peer review, Piazza, helping fellow students, track layout, etc
3. CalDay Sat. April 18 10 am @ UCB,

## Topics

- Upcoming checkpoints
- Steering control (finish)
- Telemetry logging
- Discrete Time control/timing
- Q3 line sensor
- PCB highlights
- Power conversion
  - Linear regulator
  - Buck converter

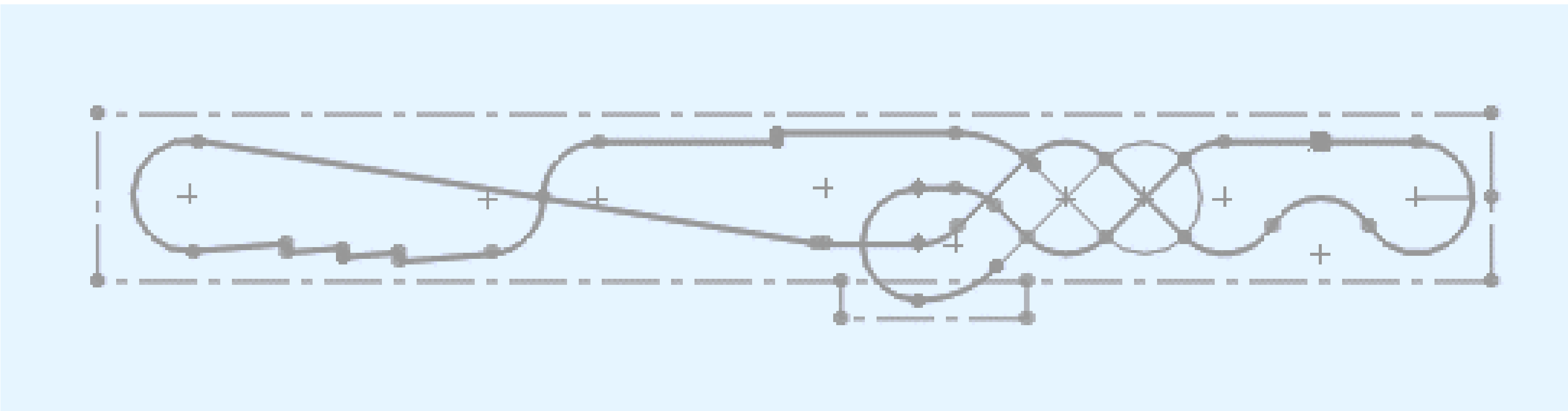
# Upcoming Checkpoints

**2/21** C4: easy, work ahead!
C4.2: Line camera image capture with exposure control.
C4.4.4 Line camera calibration: measure track lateral (static) displacement in mm
HW 1 line detection (due 3/3)

**2/28** C5: may be harder, mounting, prototyping velocity sensor, writing control code
C5.3: BBBL, motor driver, velocity sensor mounted to car
C5.4: Basic track detection and wheels turn toward track (benchtop)
C5.5: basic velocity sensor, estimation and benchtop control: 3 m/s.

**3/6** C6.3: The vehicle must complete the figure-8 course completely autonomously in under 3 minutes.
C6.3.4: running with velocity control

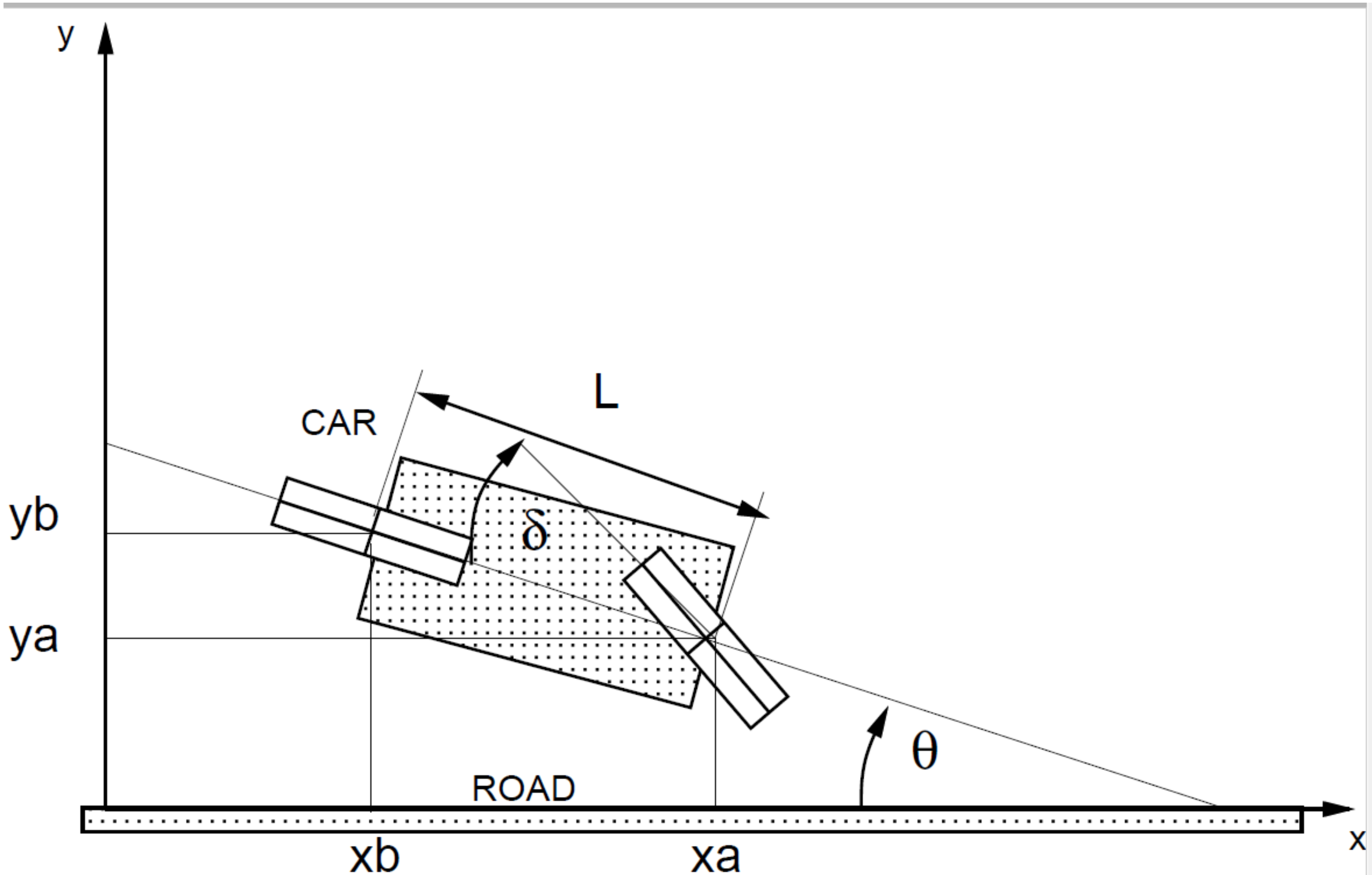
# Track Layout-
# need volunteers (time tba)



# Topics

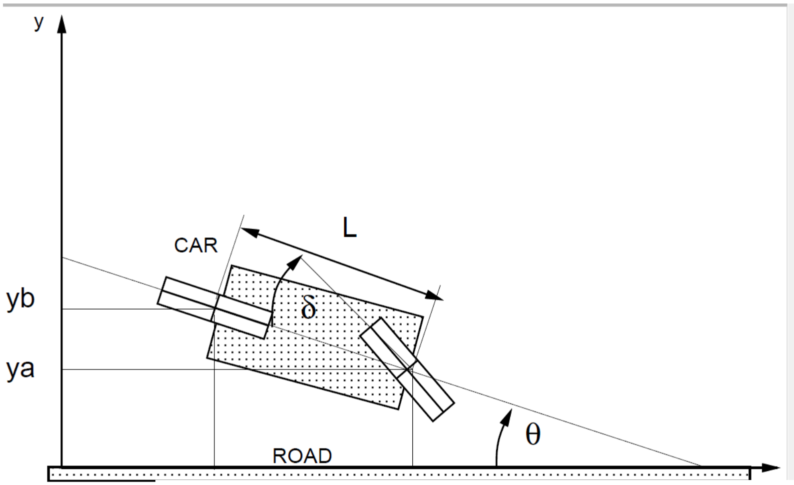
- Upcoming checkpoints
- Steering control (finish)
- Telemetry logging
- Discrete Time control/timing
- Q3 line sensor
- PCB highlights
- Power conversion
  - Linear regulator
  - Buck converter

# Bicycle Steering Model




Equations On board

# Bicycle Steering Model




Proportional control:

$$\delta(t) = k_p y_a(t)$$

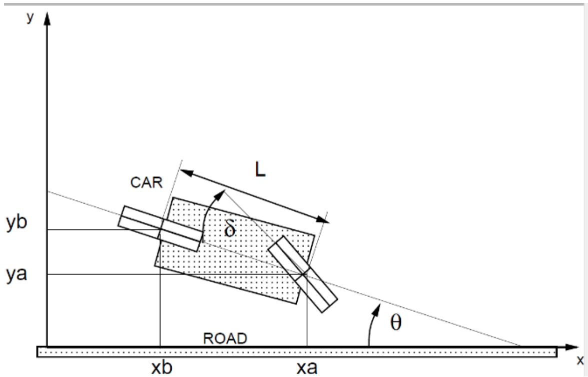
$$\ddot{y}_a + V k_p \dot{y}_a(t) + \frac{V^2}{L} k_p y_a(t) = 0.$$

Eigenvalues:

$$\lambda_{1,2} = \frac{V}{2}\left(-k_p \pm \sqrt{k_p^2 - \frac{4k_p}{L}}\right)$$

On board

# Bicycle Steering Model




Proportional control: $\delta(t) = k_p y_a(t)$

$$\ddot{y}_a + V k_p \dot{y}_a(t) + \frac{V^2}{L} k_p y_a(t) = 0.$$

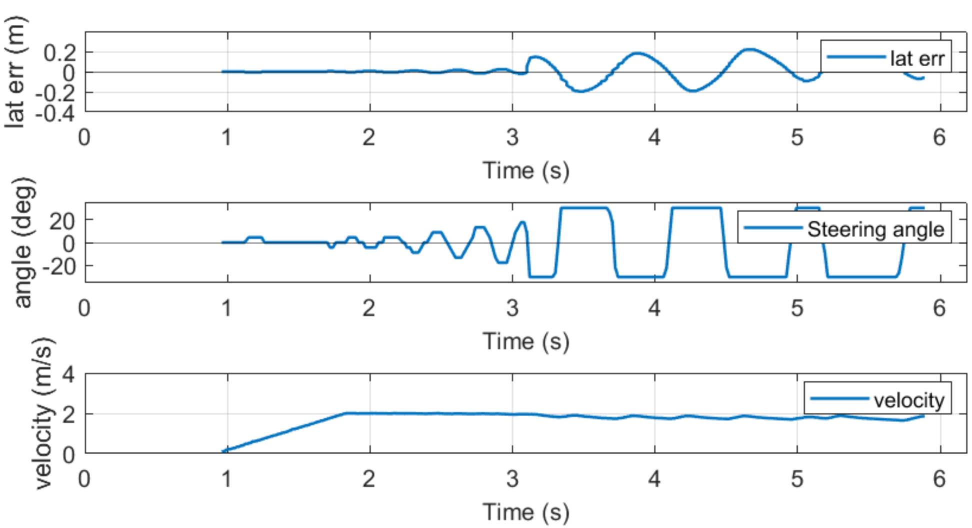
Eigenvalues: $$\lambda_{1,2} = \frac{V}{2}\left(-k_p \pm \sqrt{k_p^2 - \frac{4k_p}{L}}\right)$$

Critical damping: $\lambda_1 = \lambda_2$ ➔

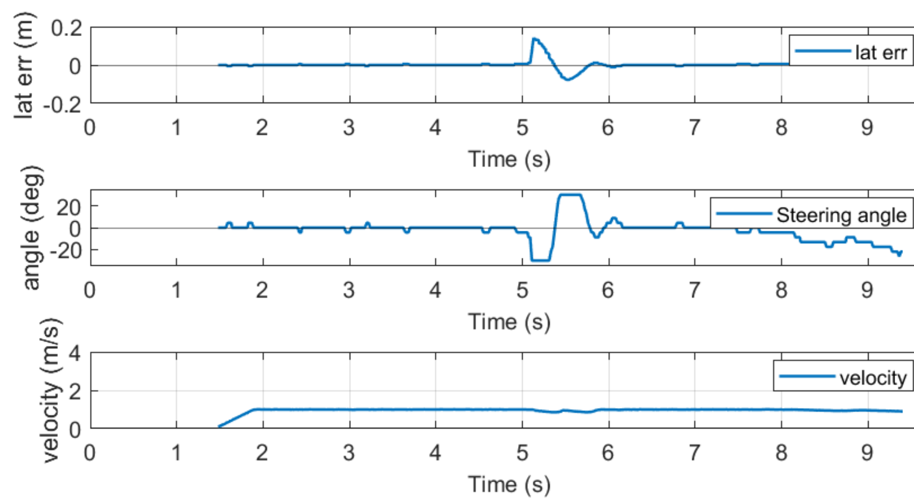
$k_p^2 = 4\ k_p/L$ or $k_p = 4/L = 4/0.3$ m = 13 rad/m = 760 deg/m

At 2 m/s, doesn't work well- servo saturates, also simulation dynamics…

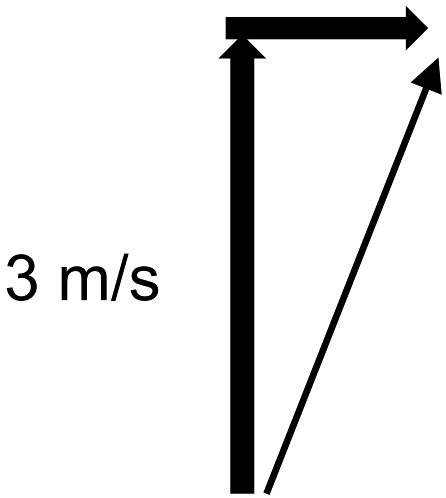
2 m/s $k_p$ =800 deg/m Kd = 0

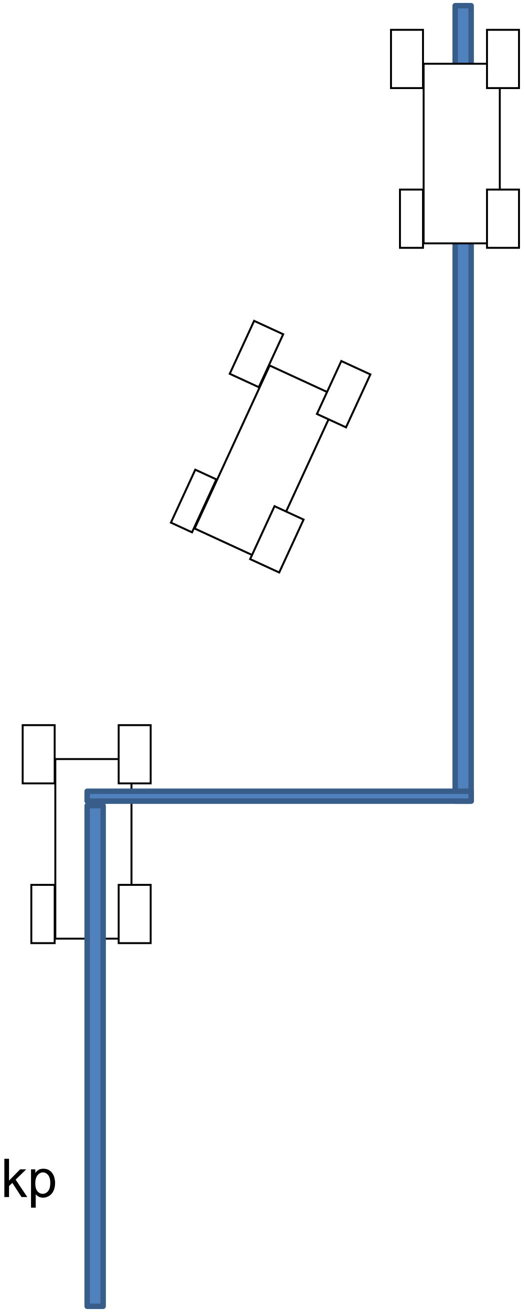



1 m/s $k_p$ =800 deg/m Kd = 0



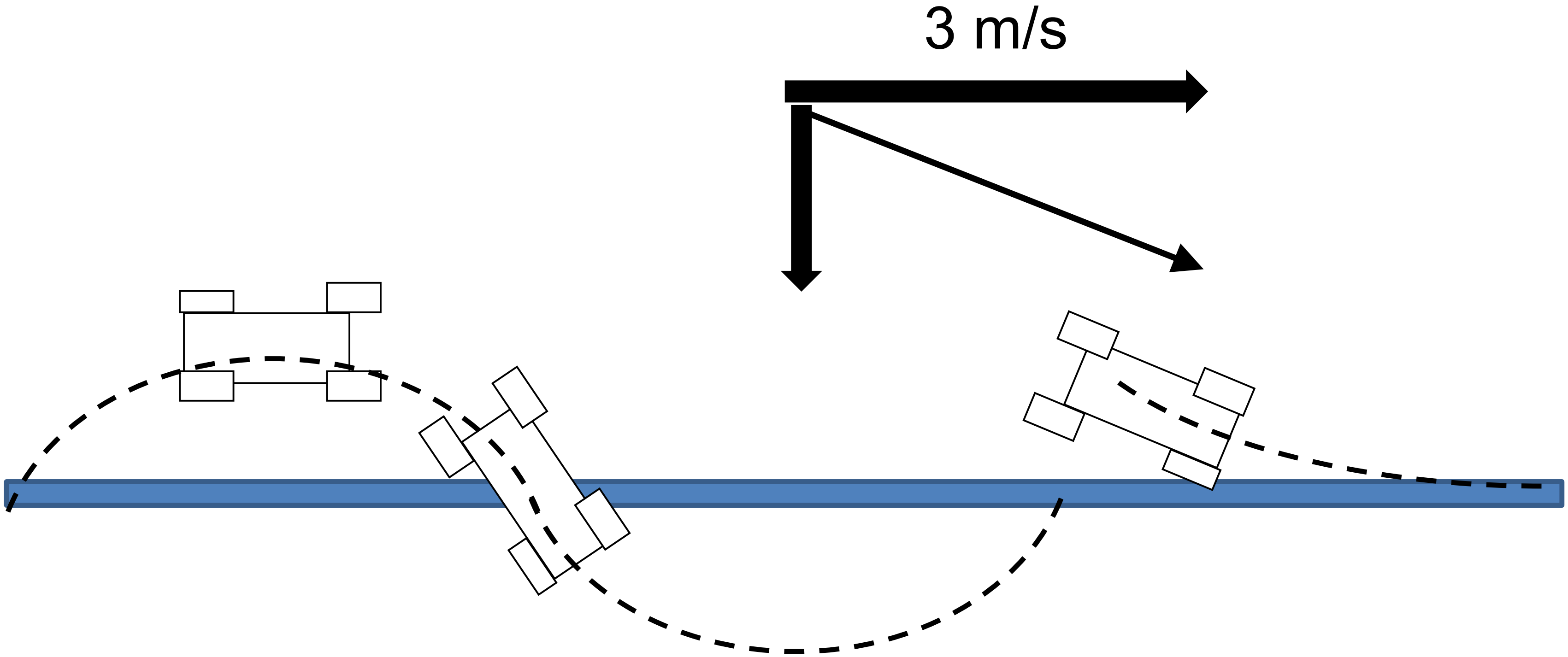
# PD parameters



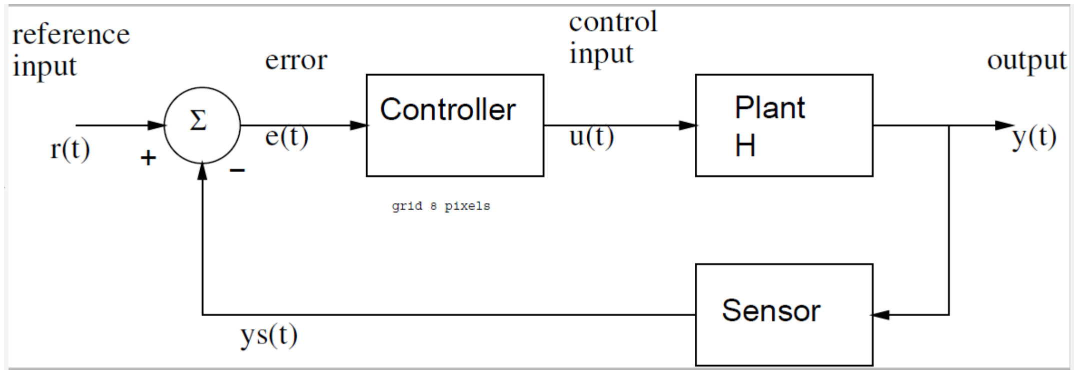
Step: 15 cm
Choose step response 1m = 300 ms
Then lateral velocity = 15 cm/300 ms = 0.5 m/sec
At mid point:
$\delta$ = 0 = kp 7.5 cm + kd 0.5 m/sec ➔ kd ~ [0.15 sec] kp

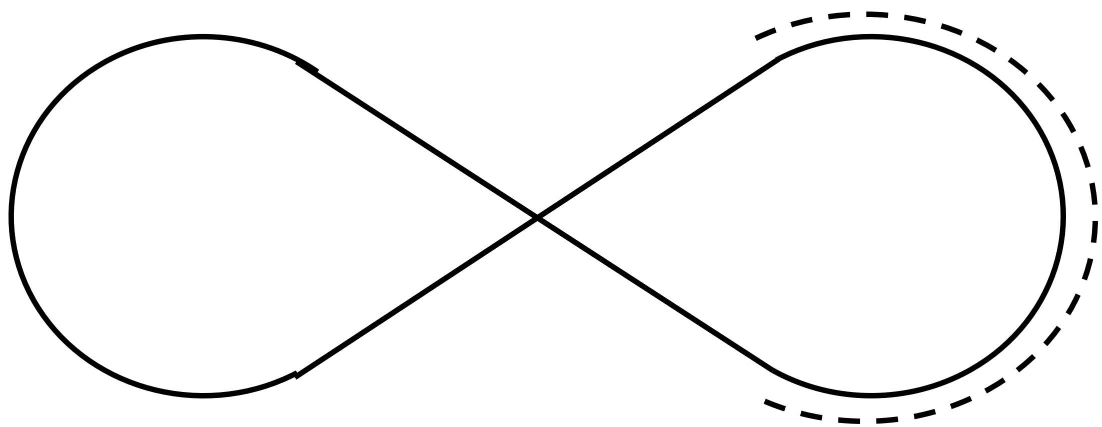
# PD parameters




Step: 15 cm
Choose step response 1m = 300 ms
Then lateral velocity = 15 cm/300 ms = 0.5 m/sec

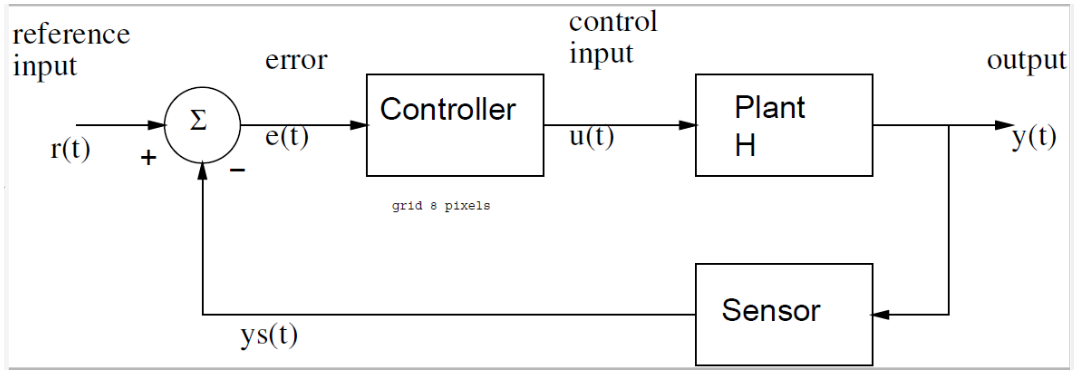
# Proportional + Integral

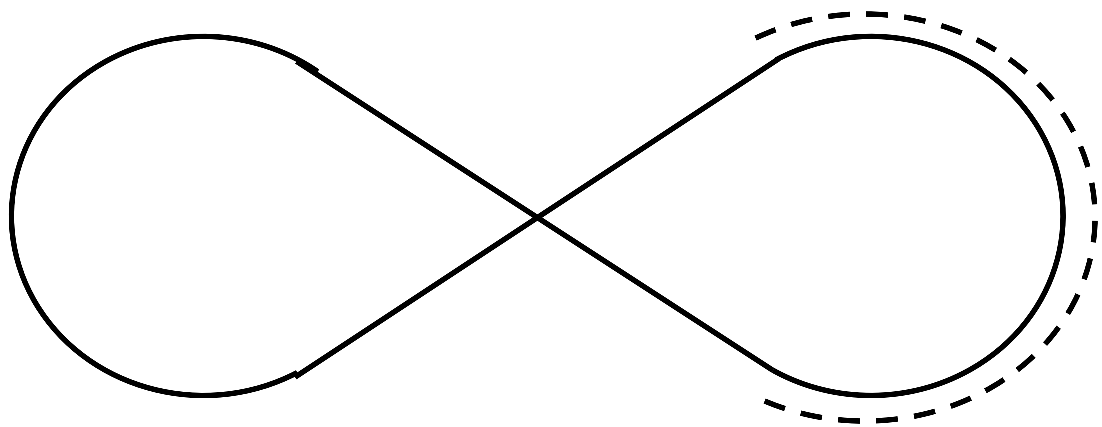


On board Anti-windup

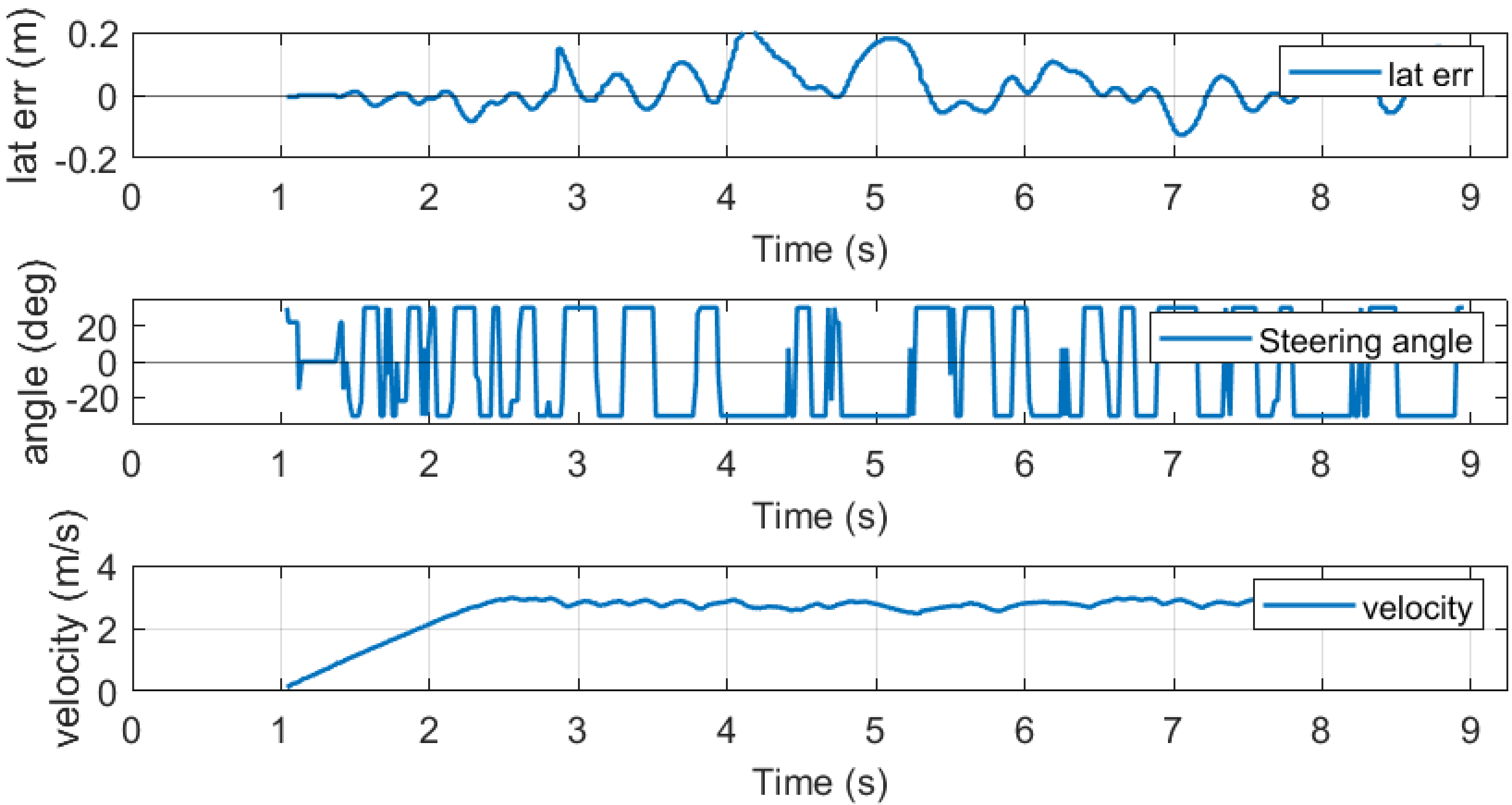
# Feedforward



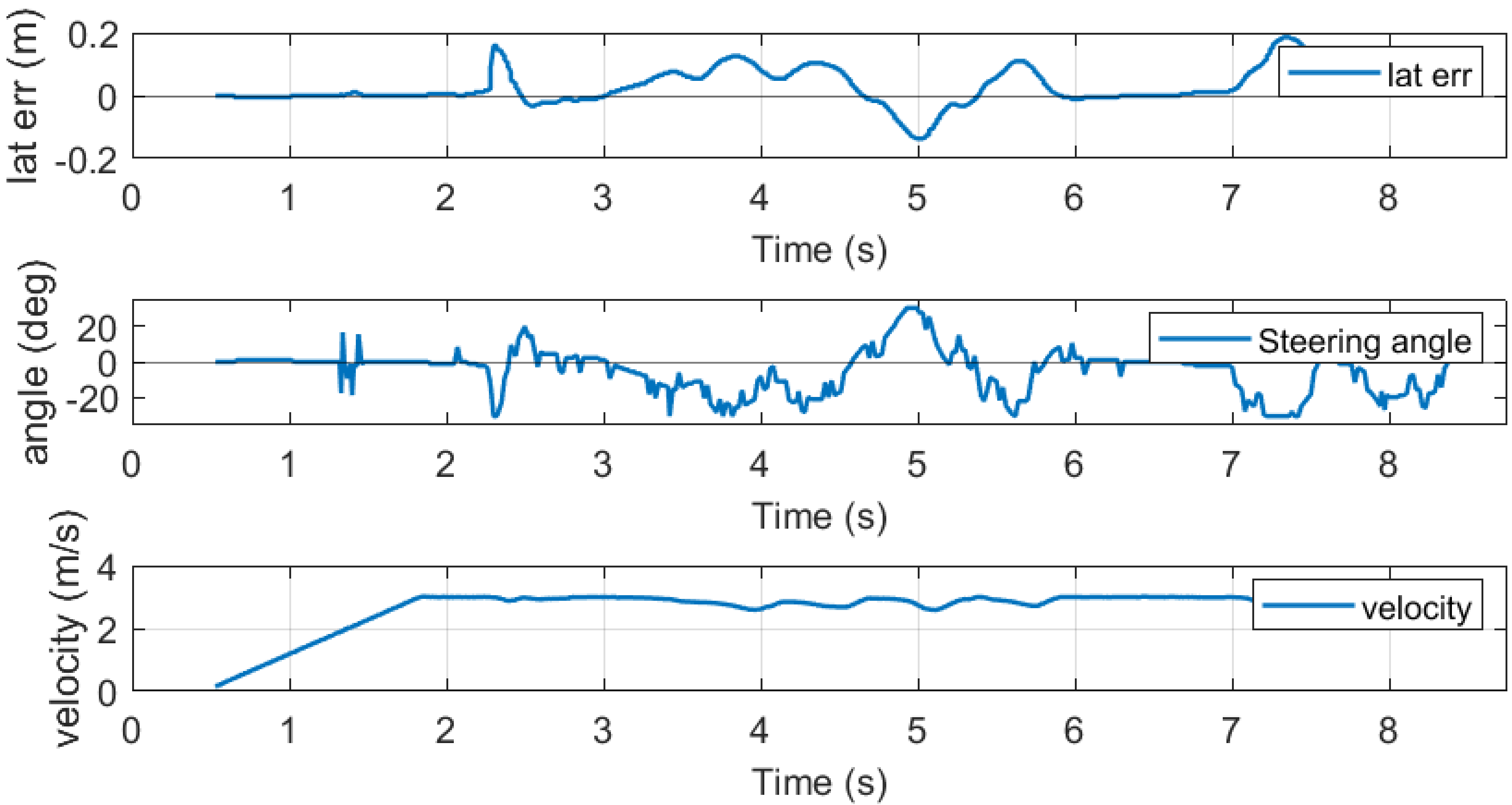



On board

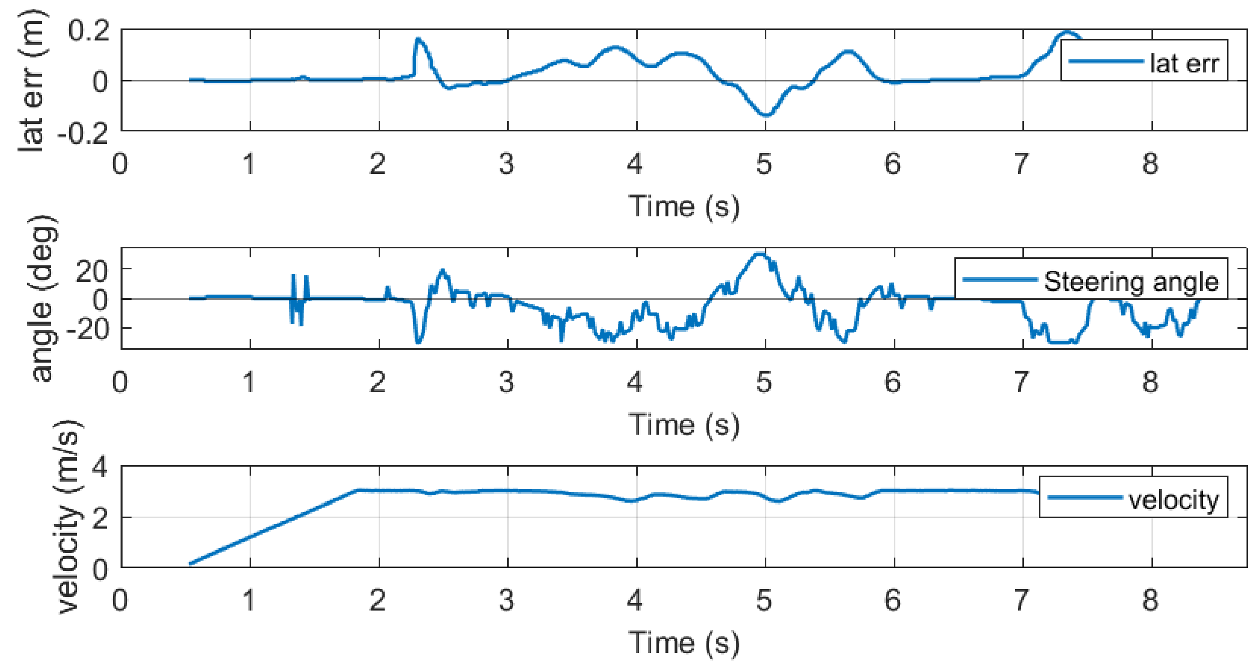
Proportional + derivative control.
Kp = 40 deg/cm, 70 rad/m
Kd = 1000 deg/(m/sec)
V=3 m/s, slew rate 600 deg/0.16 sec
NOTE: = bang-bang!
What is problem with bang bang?
Break servo, nonlinear (unstable)



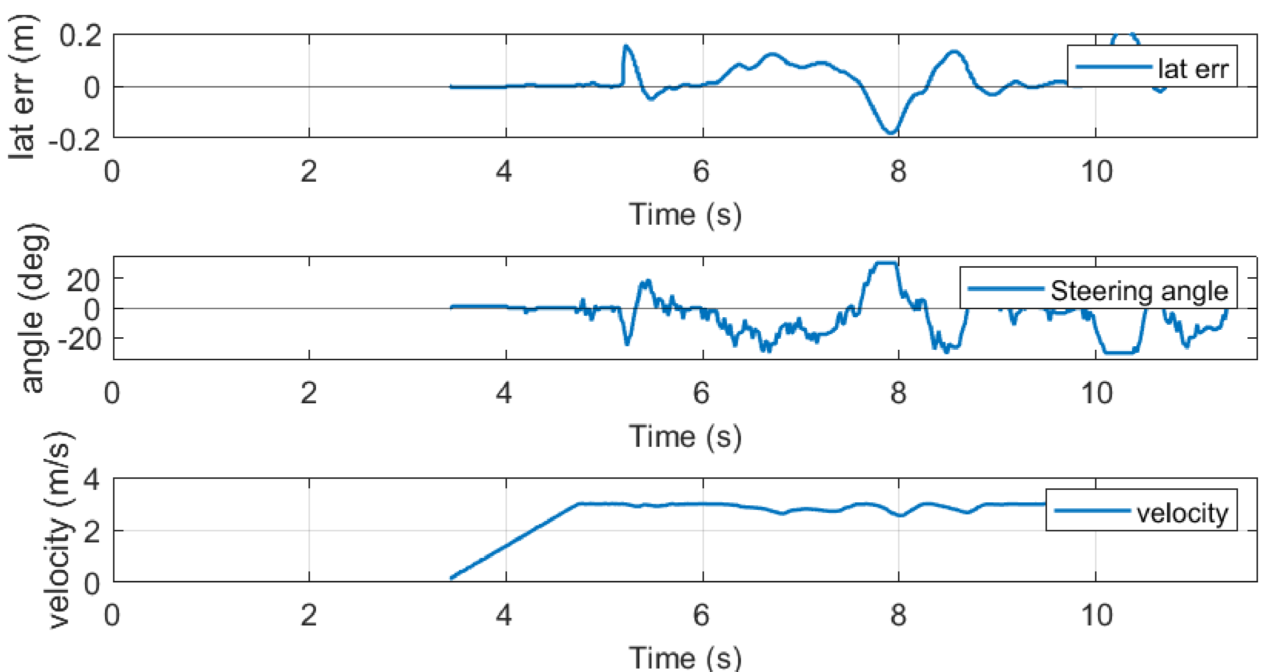
Proportional + derivative control.
Kp = 200 deg/m,
Kd = 30 deg/(m/sec) = (0.15 sec) Kp
V=3 m/s, slew rate 600 deg/0.16 sec
NOTE: = not bang-bang



Kp = 200 deg/m, Kd = 30 deg/(m/sec). V=3 m/s

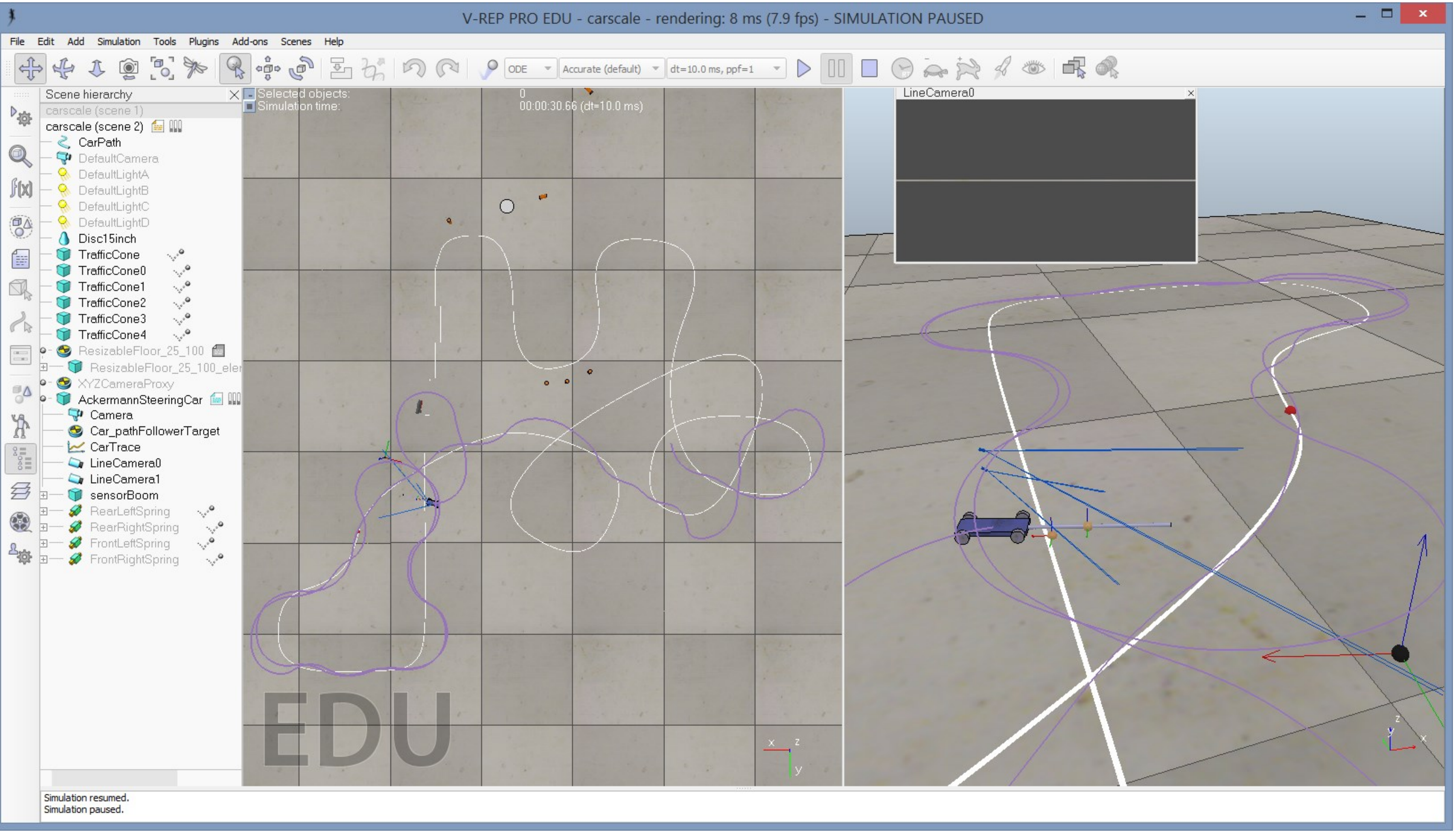



Slew 600 deg/160 ms



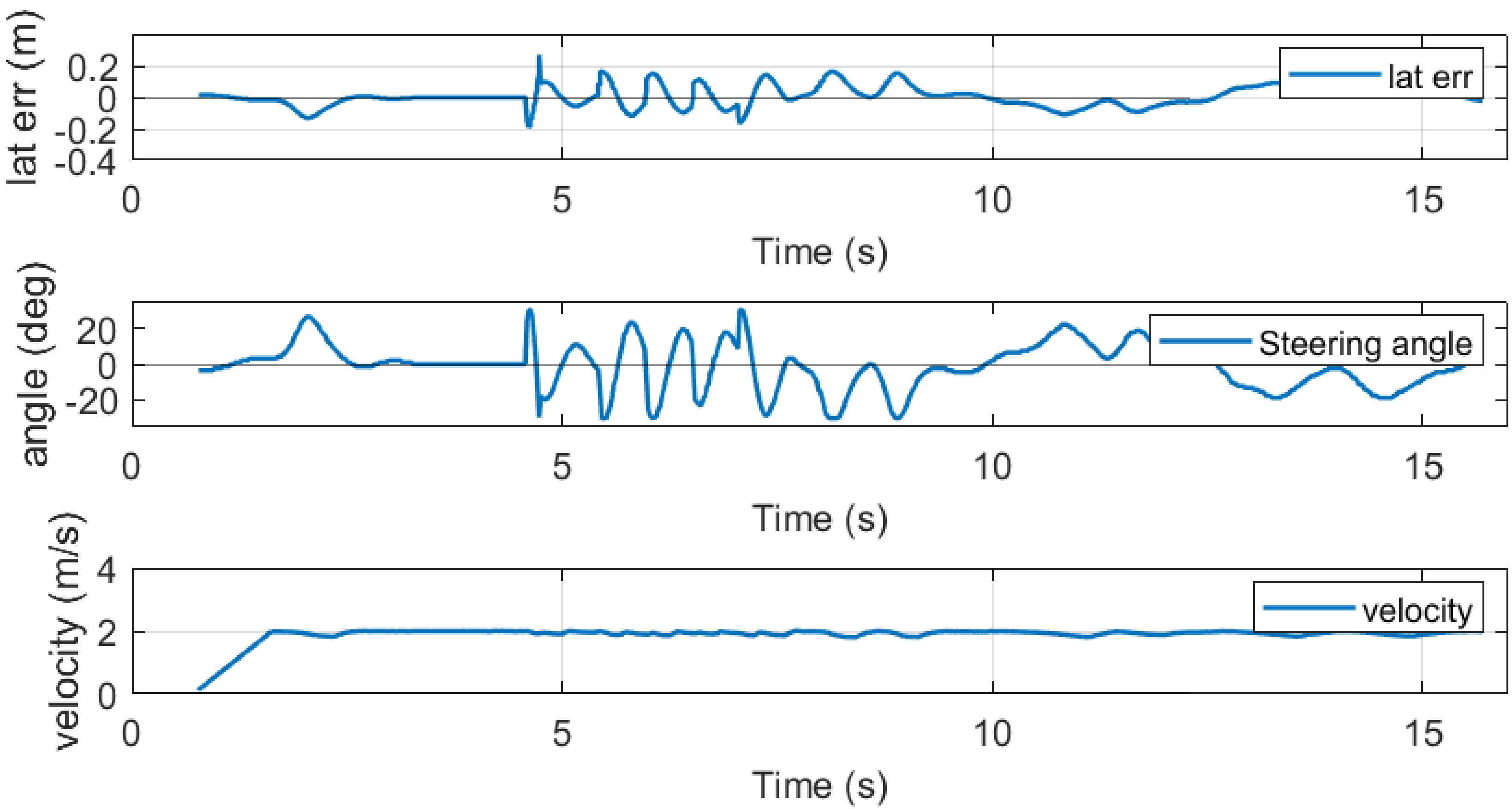

Slew 60 deg/160 ms

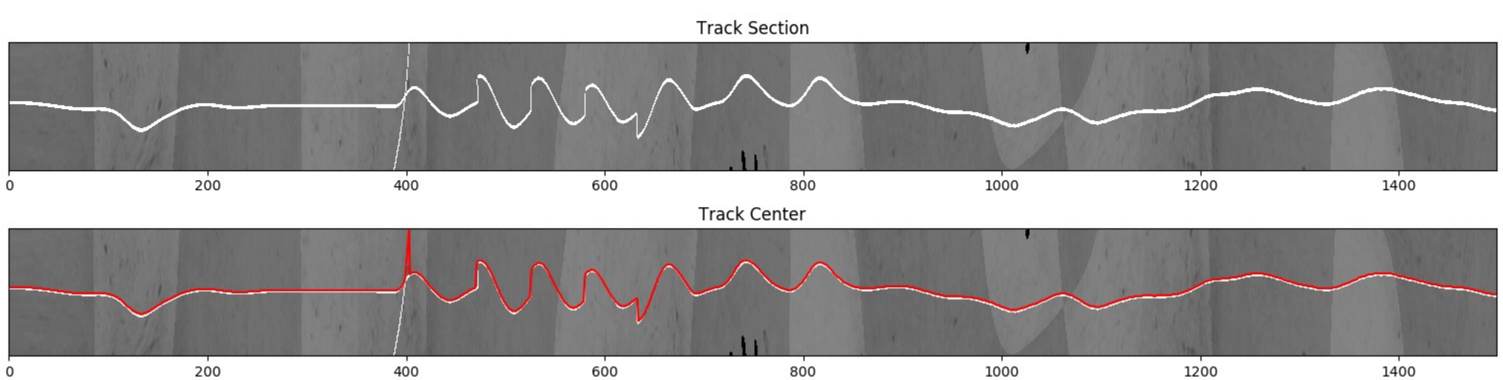
# V-rep simulation




demo

# V-rep simulation



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# TimingTest.c: how long does fprintf take?

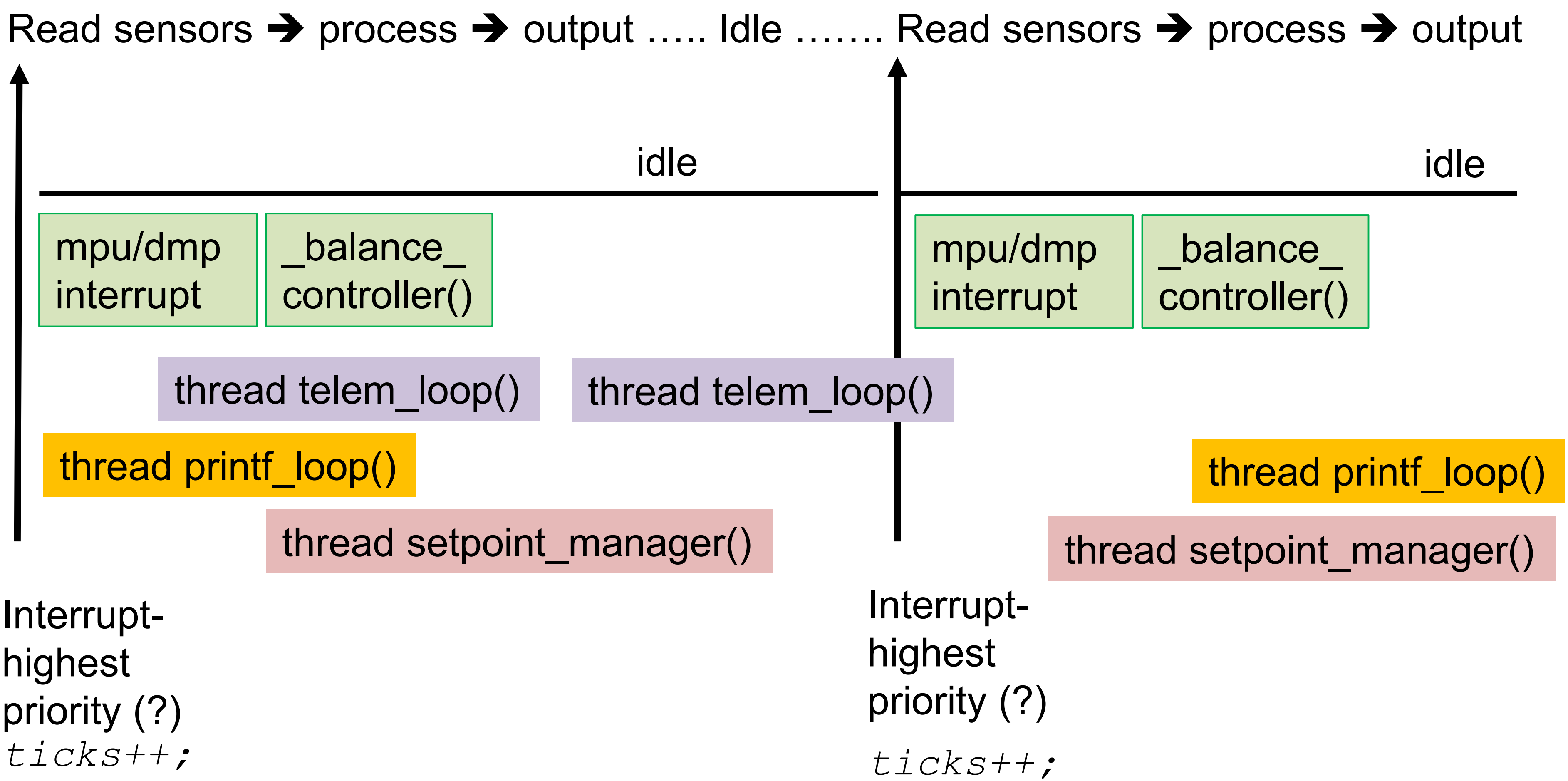
```
while(rc_get_state()!=EXITING)
{  // just data for csv format
        current_time = rc_nanos_since_boot() - start_time;
        old_tick = ticks;
        fprintf(logfile, "%ld, ", old_tick);  // pass value which not changing by other process
        current_time_f = ((double) current_time)/ 1e6; // milliseconds
        run_time_f = ((double) run_time)/1000.0; // us

        fprintf(logfile,"%8.3lf, %8.3lf, ", current_time_f, run_time_f);
        fprintf(logfile, "%" PRIu64 ", ",current_time);
        fprintf(logfile, "%" PRIu64 "\n",run_time);

        end_time = rc_nanos_since_boot() - start_time;
        run_time = end_time - current_time;
        while(old_tick == ticks)
        { rc_usleep(100); // sleep 100 us
        }
  }
```

run_time:  min 20 us, typical 30-50 us, max 6600 us

# Software Notes




Threads are asynchronous wrt interrupt!

**`rc_pthread_set_process_niceness()`** **?**

# rc_balance2.c using gyro/MPU

When new data is ready in the buffer, the IMU sends an interrupt to the BeagleBone triggering the buffer read followed by the execution of a function of your choosing set with the rc_mpu_set_dmp_callback() function.

```
// set up mpu configuration
rc_mpu_config_t mpu_config = rc_mpu_default_config();
mpu_config.dmp_sample_rate = SAMPLE_RATE_HZ;

// start mpu
if(rc_mpu_initialize_dmp(&mpu_data, mpu_config))

// this should be the last step in initialization
// to make sure other setup functions don't interfere
rc_mpu_set_dmp_callback(&__balance_controller);

// idle while sensing and control done elsewhere
while(rc_get_state()!=EXITING){
      rc_usleep(200000);  }
```

# rc_balance2.c __balance_controller()

```
static void __balance_controller(void)
{ticks++;
 end_time = rc_nanos_since_boot();
 run_time = end_time - start_time;
// time since previous interrupt

/*************************************************************
* STATE_ESTIMATION
* read sensors and compute the state
*************************************************************/
cstate.wheelAngleL =
(rc_encoder_eqep_read(ENCODER_CHANNEL_L) * 2.0 * M_PI) \
/(ENCODER_POLARITY_L * GEARBOX * ENCODER_RES);
/*****************************************************
* Send signal to motors
*****************************************************/
dutyL = cstate.d1_u - cstate.d3_u;
rc_motor_set(MOTOR_CHANNEL_L, MOTOR_POLARITY_L * dutyL);
}
```

# rc_balance2.c: threads

*// Note that using anything other than SCHED_OTHER with priority 0 is only available to root*

**int** main(**int** argc, **char** *argv[])
{ int c;
  pthread_t setpoint_thread = 0;
  pthread_t printf_thread = 0;
  pthread_t telem_thread = 0;
…

// print thread to print to screen without blocking main

```
rc_pthread_create(&printf_thread, __printf_loop, (void*) NULL,
SCHED_OTHER, 0);
```

…

// start balance stack to control setpoints

```
rc_pthread_create(&setpoint_thread, __setpoint_manager,
(void*) NULL, SCHED_OTHER, 0);
```

…

// telemetry thread to log to file

```
rc_pthread_create(&telem_thread, telem_loop, (void*) NULL,
SCHED_OTHER, 0);
// telem loop could write to file
```

# Example logging thread

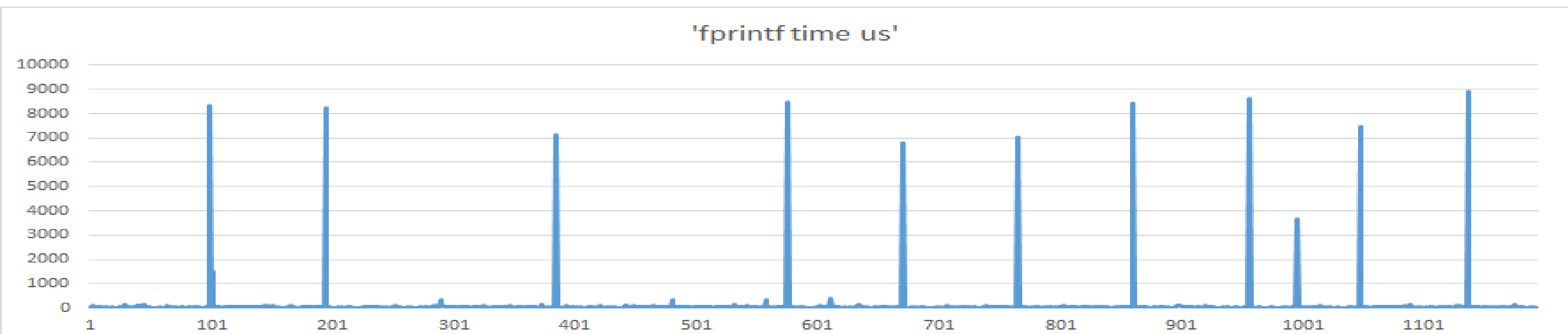
// telemetry thread to log to file

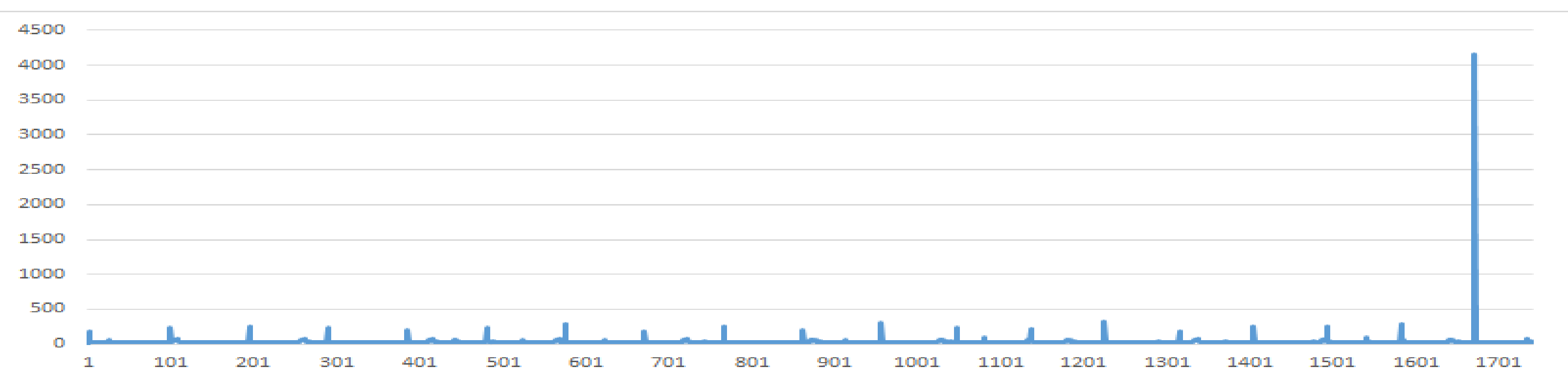
```
void* telem_loop(__attribute__ ((unused)) void* ptr)
{       long old_tick=0; uint64_t initial_time, current_time;
        printf("telem thread\n"); fflush(stdout); // empty buffer
        initial_time = rc_nanos_since_boot();
        while(rc_get_state()!=EXITING)
        {       current_time = rc_nanos_since_boot();
                old_tick = ticks;
                fprintf(logfile, "%ld, ", old_tick);  // pass value
which not changing by other process
                fprintf(logfile, "%10.3f, ",
                        (double)(current_time-initial_time)/1e6);
                fprintf(logfile,"%8.3f, ", cstate.yaw);
                fprintf(logfile,"%8.3f, %8.3f",
                        cstate.dutyL, cstate.dutyR);
                fprintf(logfile, "%8.3f\n", cstate.vBatt);
                while(old_tick == ticks)
                { rc_usleep(100); // sleep 100 us
                }
        }
        rc_usleep(1000000 / PRINTF_HZ);
        return NULL;
}
```

# Debian Processes/Delay

```
htop
# systemctl disable avahi-daemon
# systemctl stop avahi-daemon


sudo kill -9 {avahi-daemon, rc_battery_monitor,
apache2}.
```



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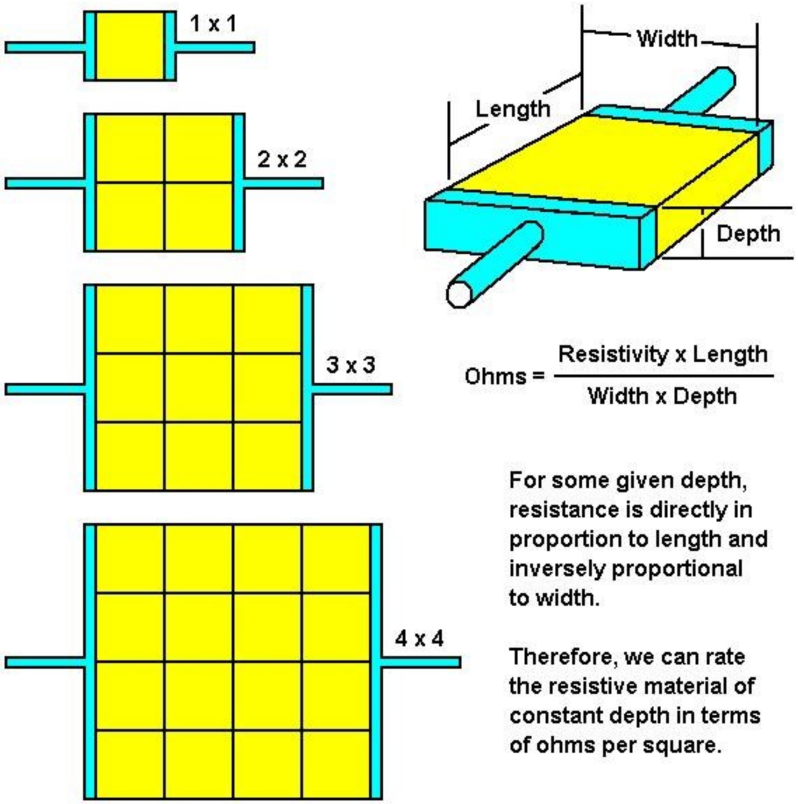
# Ohms/square




$$\text{Ohms} = \frac{\text{Resistivity x Length}}{\text{Width x Depth}}$$

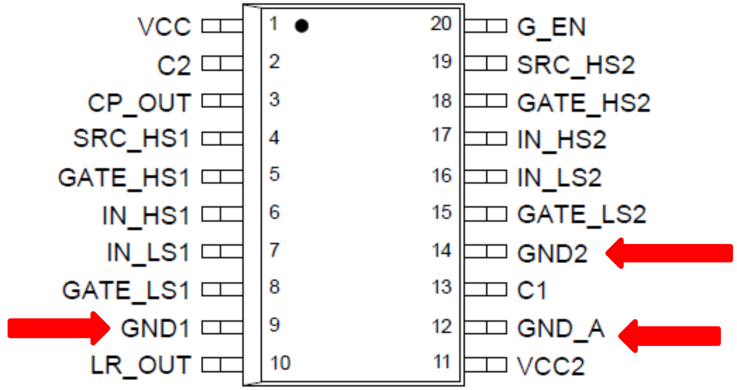
For some given depth, resistance is directly in proportion to length and inversely proportional to width.

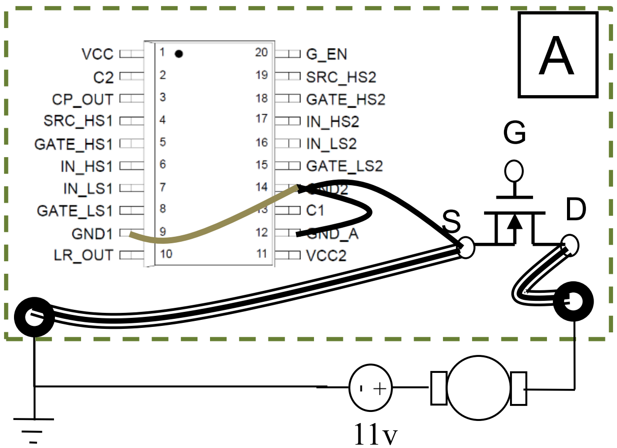
Therefore, we can rate the resistive material of constant depth in terms of ohms per square.

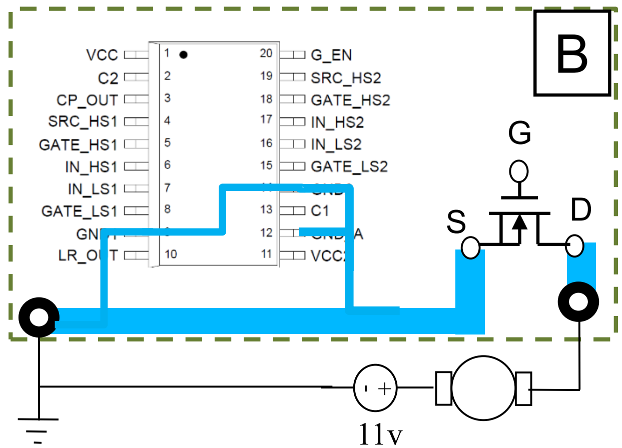
| Cu Weight oz. | Thickness mm(mils) | mΩ/Square 25°C | mΩ/Square 100°C |
|---|---|---|---|
| 1/2 | .02 (0.7) | 1.0 | 1.3 |
| 1 | .04 (1.4) | 0.5 | 0.65 |
| 2 | .07 (2.8) | 0.25 | 0.36 |
| 4 | .13 (5.3) | 0.13 | 0.18 |

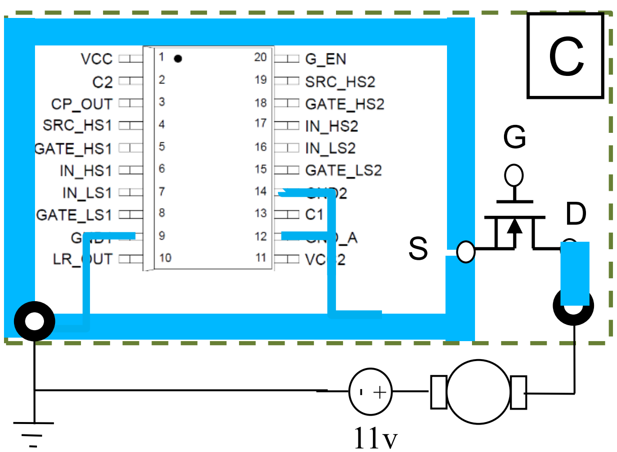
http://www.edn.com/design/components-and-packaging/4411971/Counting-squares--A-method-to-quickly-estimate-PWB-trace-resistance

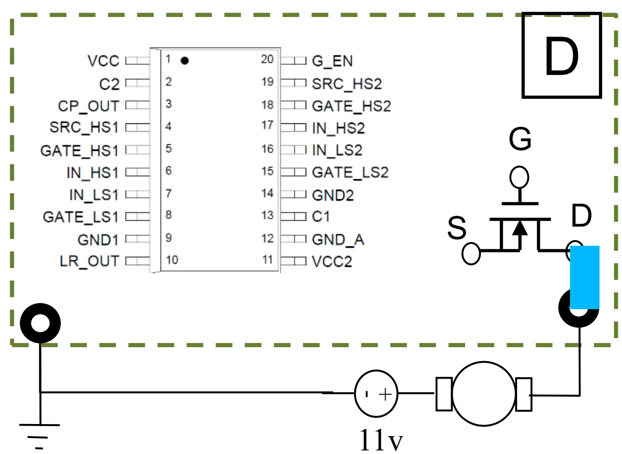
# Power supplies and Wiring

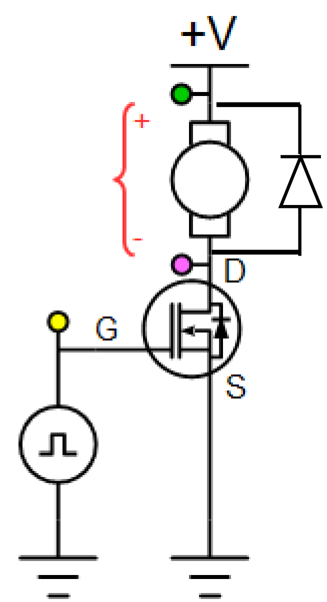


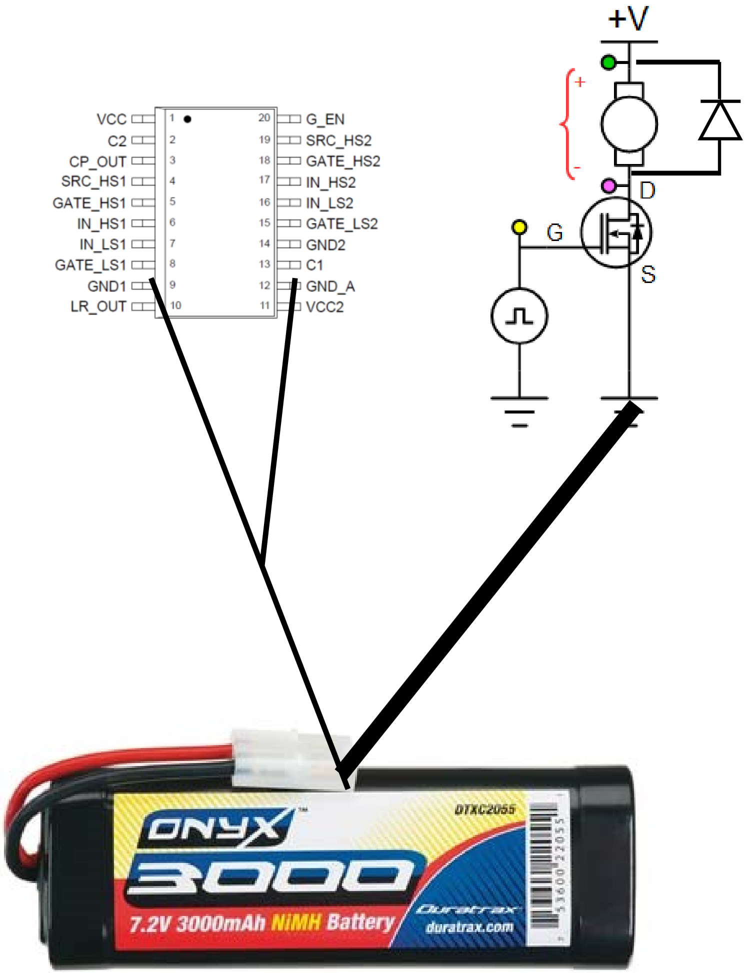



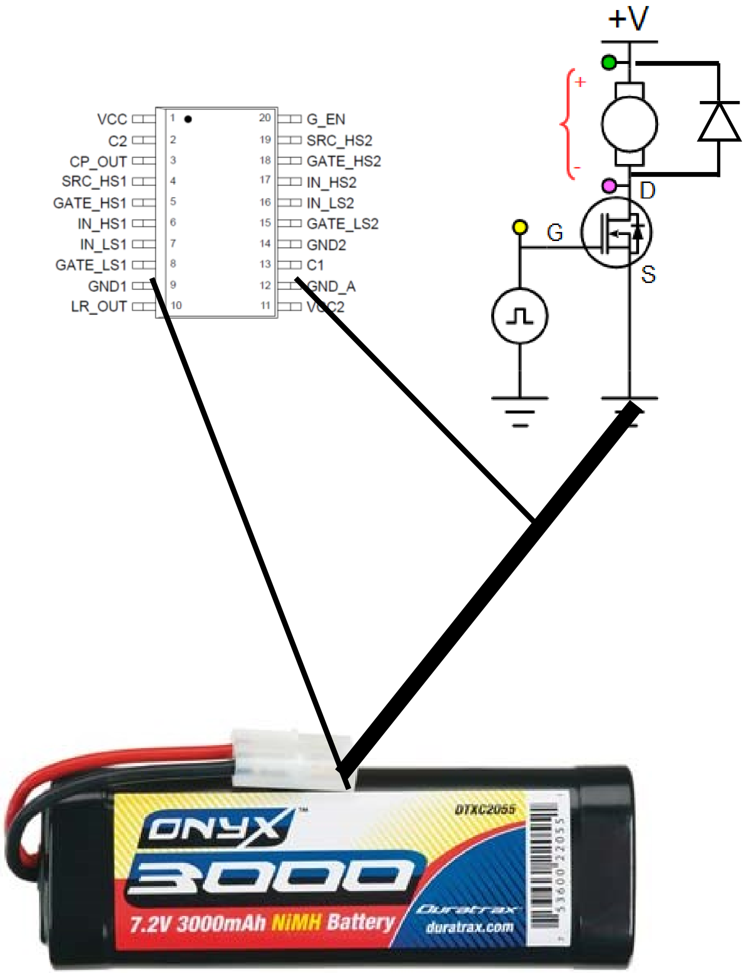



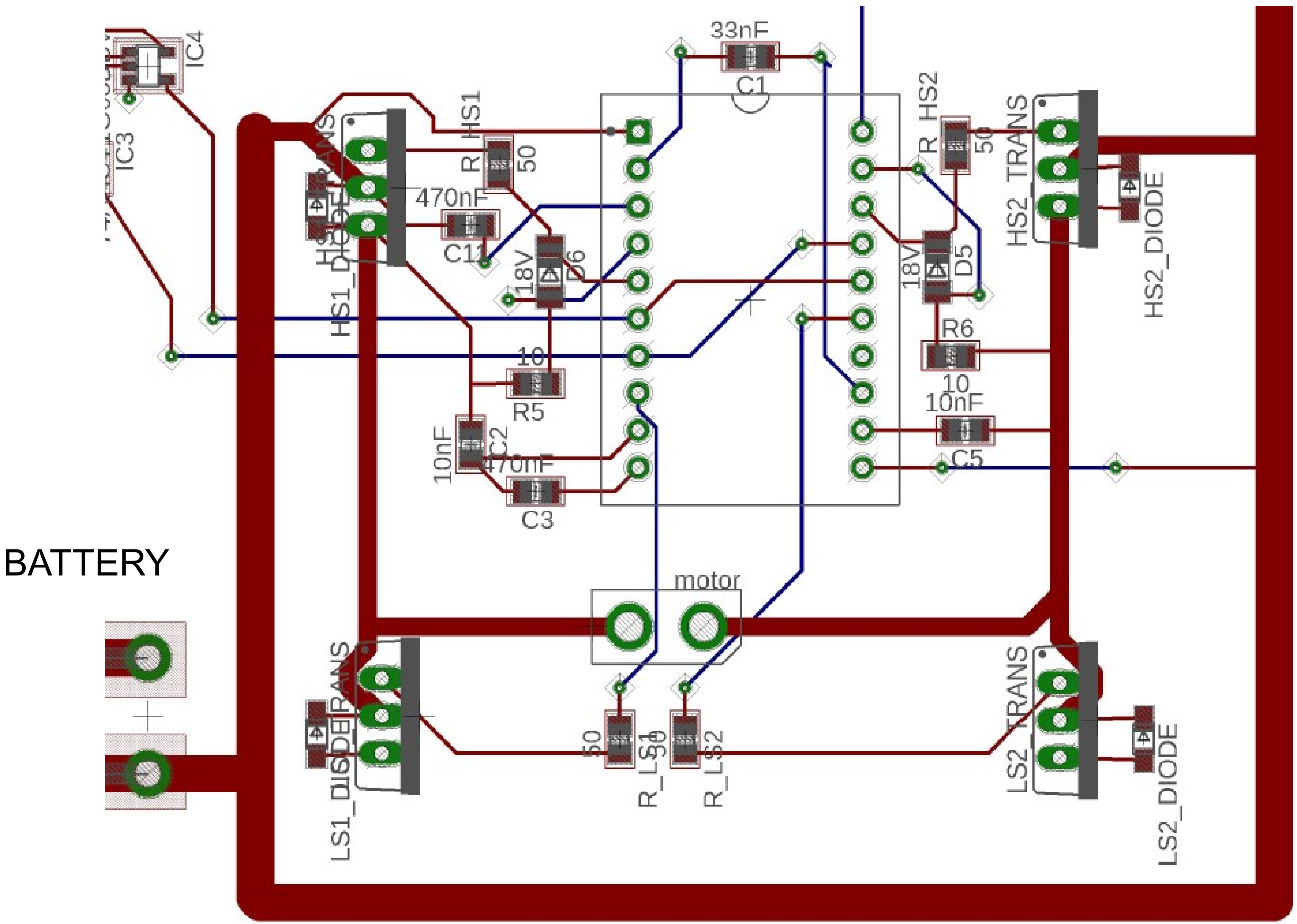
Which is ``Star" config?




wiring

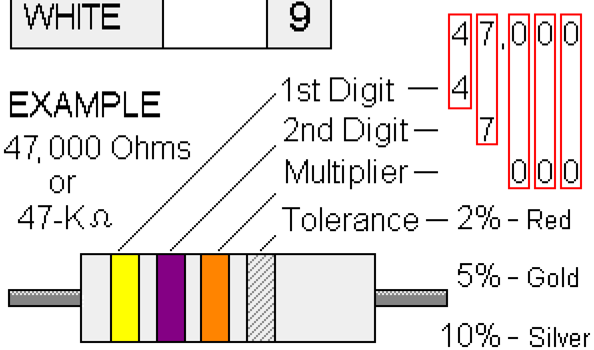
# PCB Notes



IC4
IC3
33nF
C1
R_HS1
50
470nF
C11
18V
D6
10
R5
10nF
C2
470nF
C3
HS1_DIODE
HS1_TRANS
R_HS2
50
HS2_TRANS
HS2_DIODE
18V
D5
R6
10
10nF
C5
BATTERY
motor
LS1_TRANS
LS1_DIODE
50
R_LS1
50
R_LS2
LS2_TRANS
LS2_DIODE

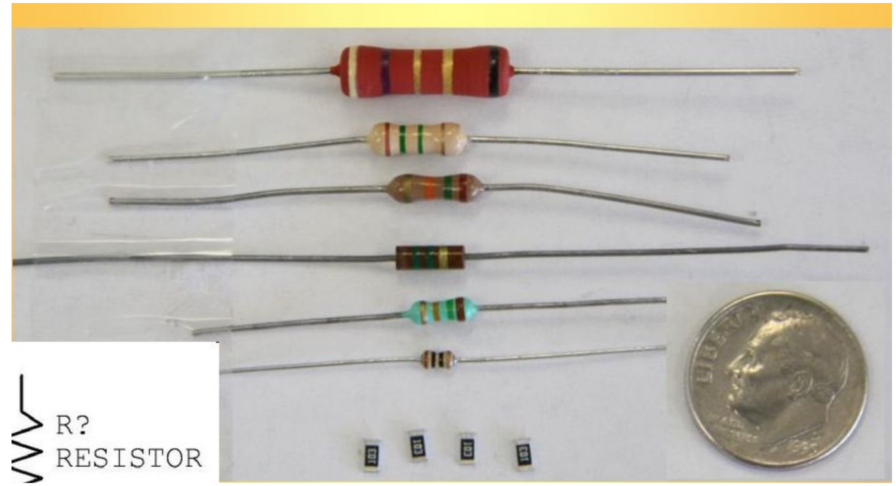
# Electronic Components- Resistors

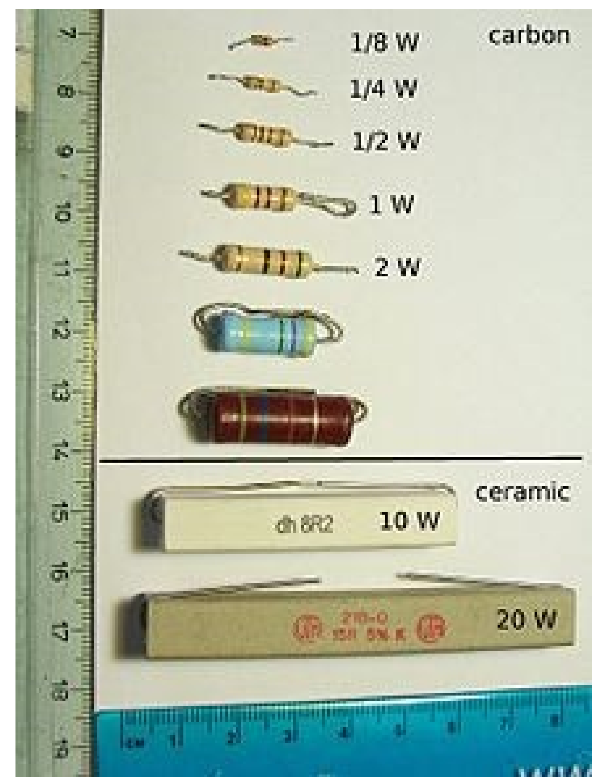
| | | | Multiplier |
|---|---|---|---|
| BLACK | | 0 | ________ |
| BROWN | | 1 | _______0 |
| RED | | 2 | ______00 |
| ORANGE | | 3 | ____000 |
| YELLOW | | 4 | __0, 000 |
| GREEN | | 5 | _00, 000 |
| BLUE | | 6 | 000, 000 |
| VIOLET | | 7 | |
| GRAY | | 8 | |
| WHITE | | 9 | |




Yellow | violet | orange| gold

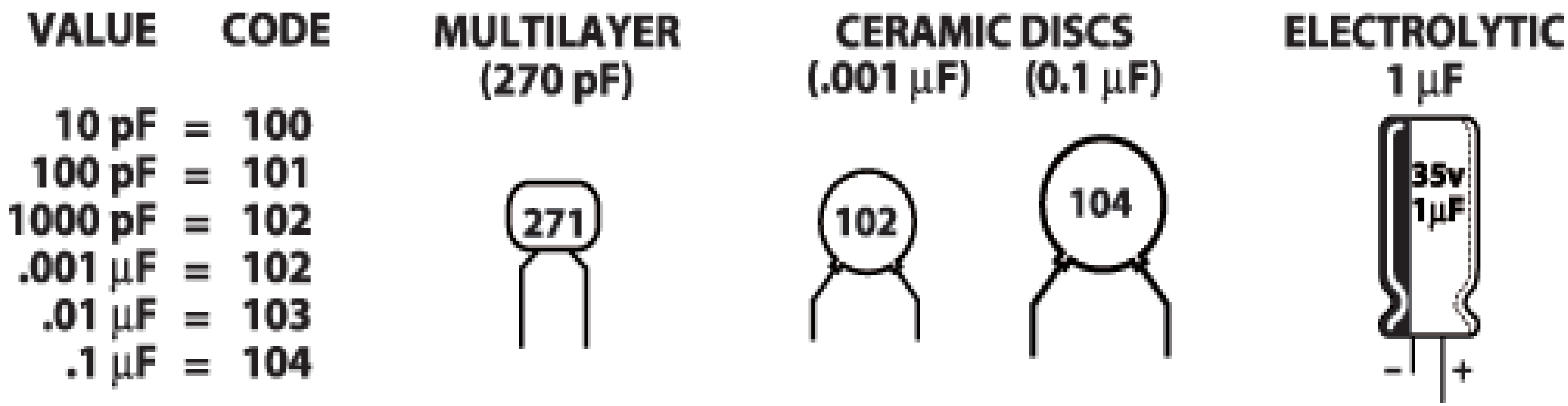
Better be right or your great big venture goes west…



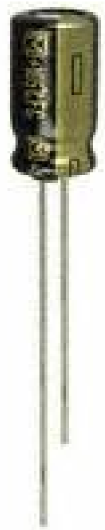



# Capacitor Codes

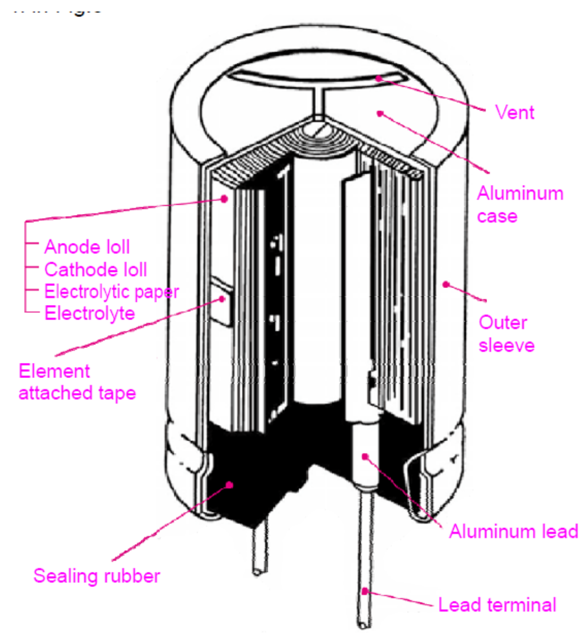
From:http://www.applefritter.com/sites/default/meta/replicacreation/images/fige-10.png



# Capacitor Types- 47 uF 50V

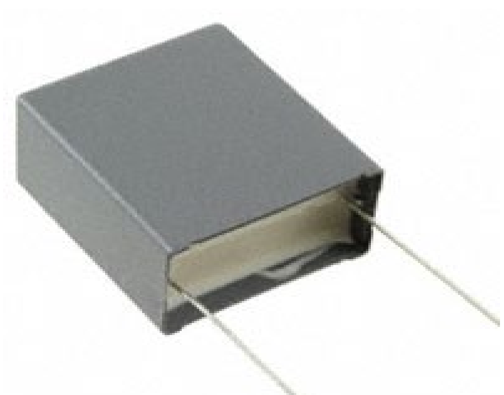


Ripple Current
600mA




Eletrolytic Ripple Current
169mA @ 120Hz

https://industrial.panasonic.com



Metalized film

CAP TANT 22UF 50V
20% 2917

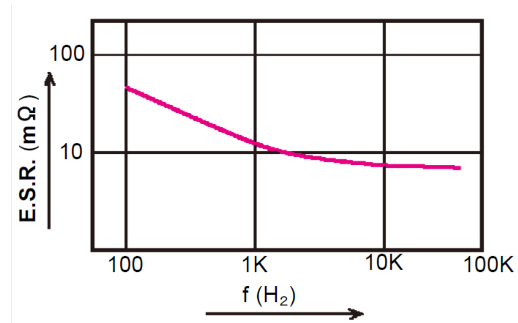
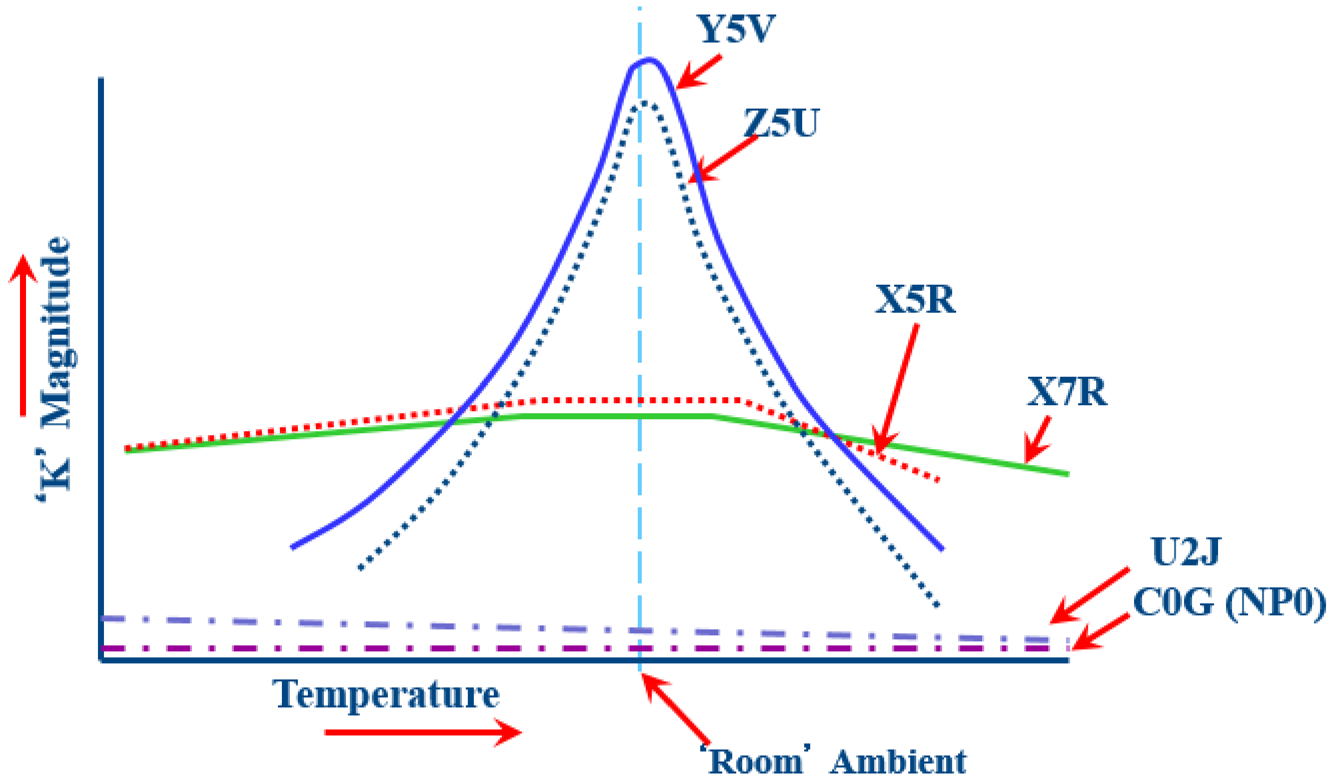



Fig.13 ESR vs frequency

# Capacitor Types-ceramic

CAP CER 0.1UF 50V X7R
RADIAL

0.1µF ±20% 50V Ceramic
Capacitor Z5U Radial




https://ec.kemet.com/wp-content/uploads/2015/12/ceramic-dielectric-comparison-chart.png

CAP CER 0.1UF 630V X7R RADIAL

CAP CER 0.1UF 50V X7R 0805

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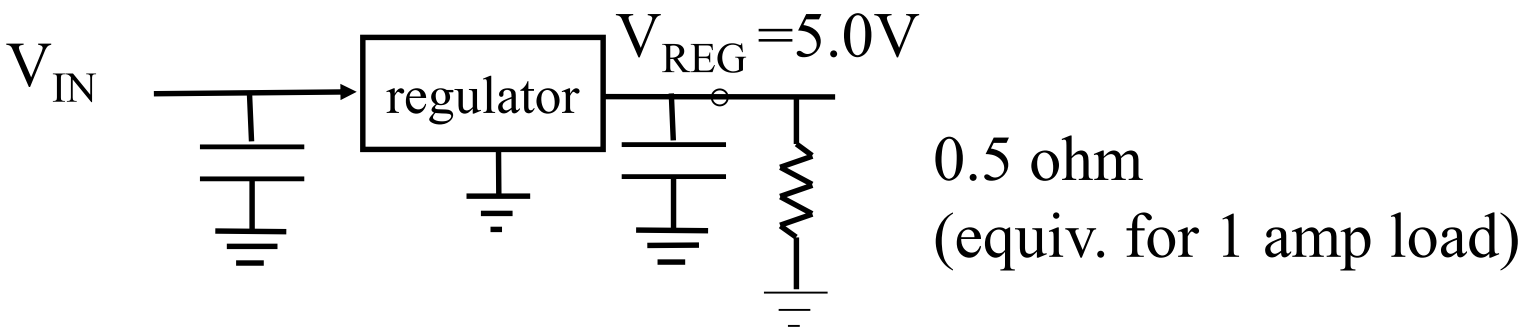
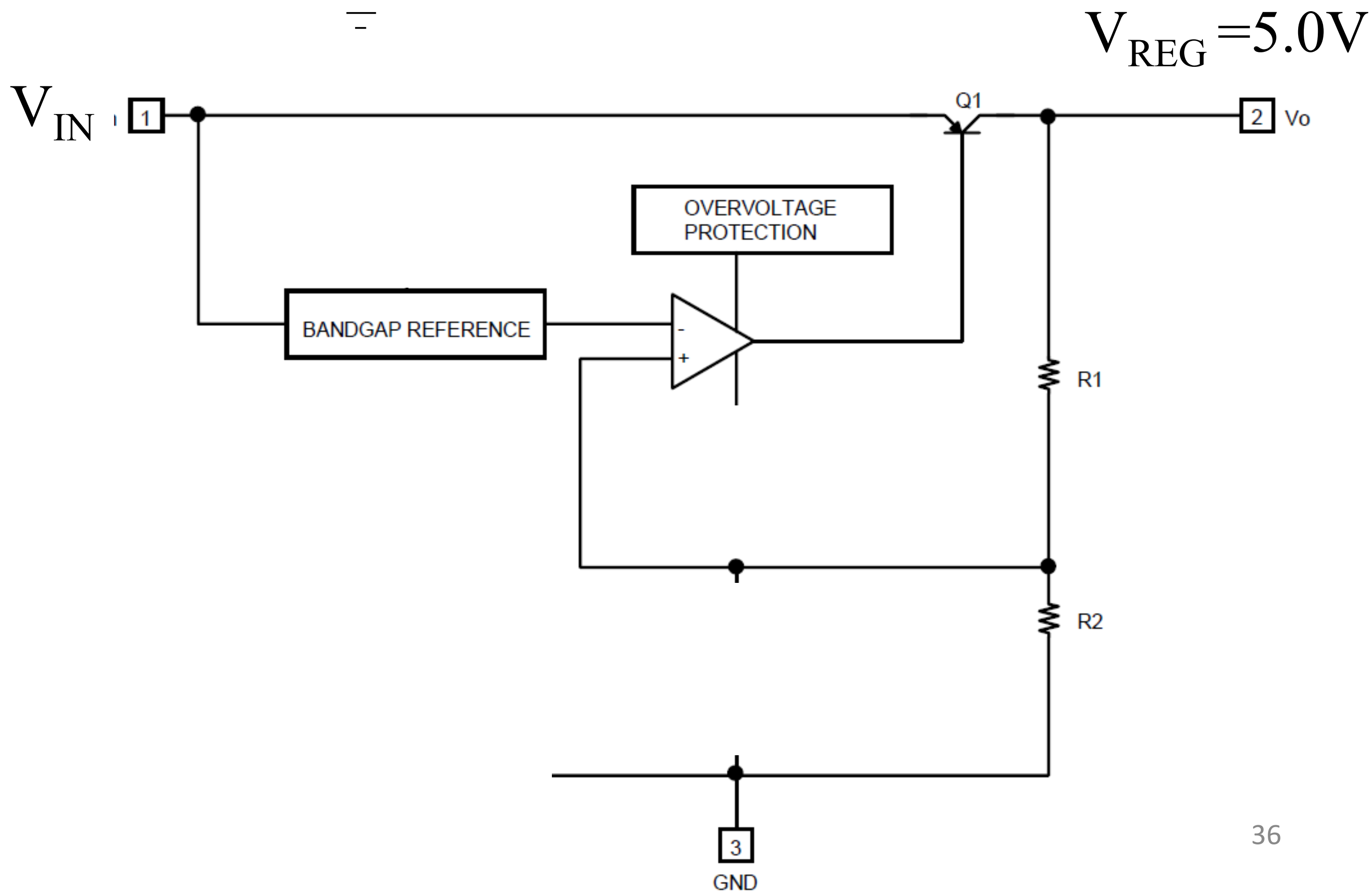
  - Buck converter

# Linear Voltage Regulator

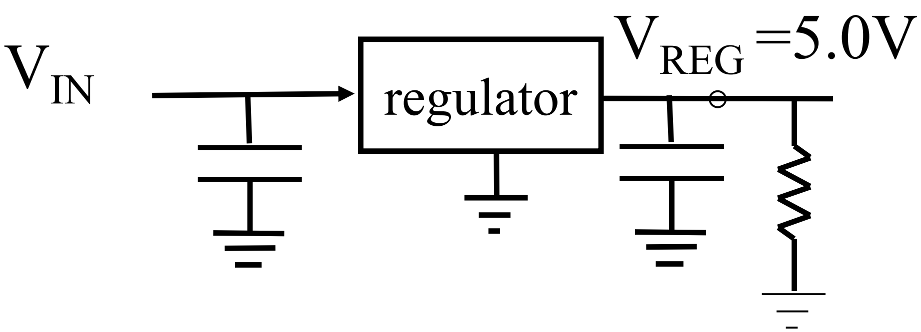


# Linear Regulator for RC servo power

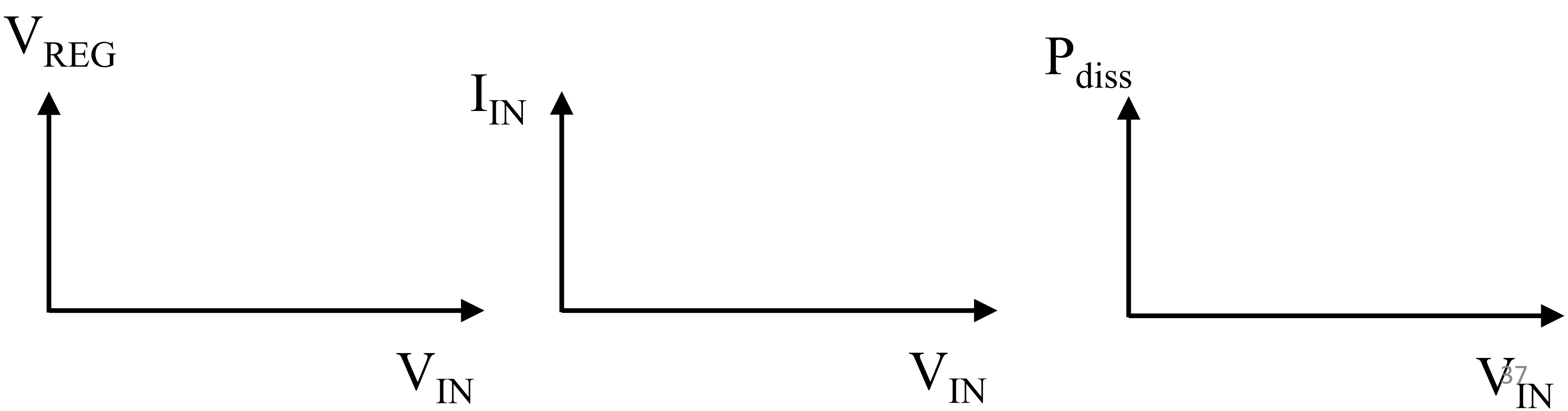
- Power limit? Heat….

Caution: caps required for stability for some voltage regulators

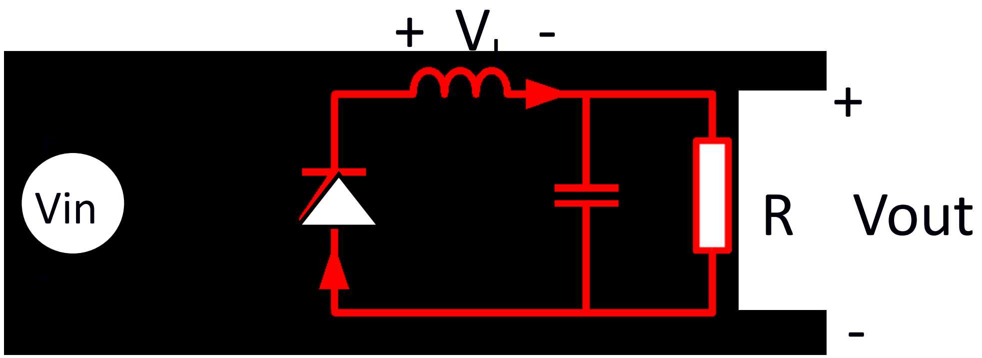



5 ohm
(equiv. for 1 amp load)

$P_{diss}$ =?



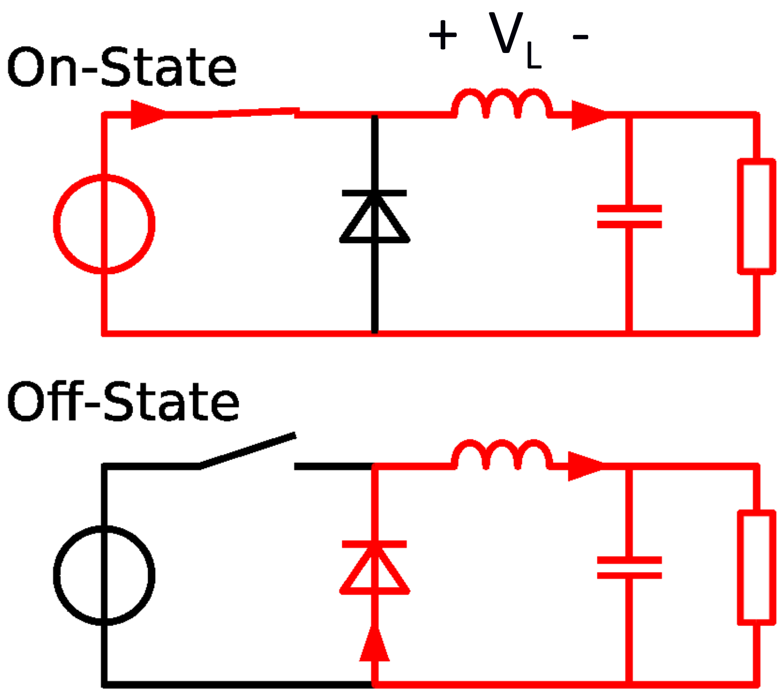
# Buck Converter- DC-DC

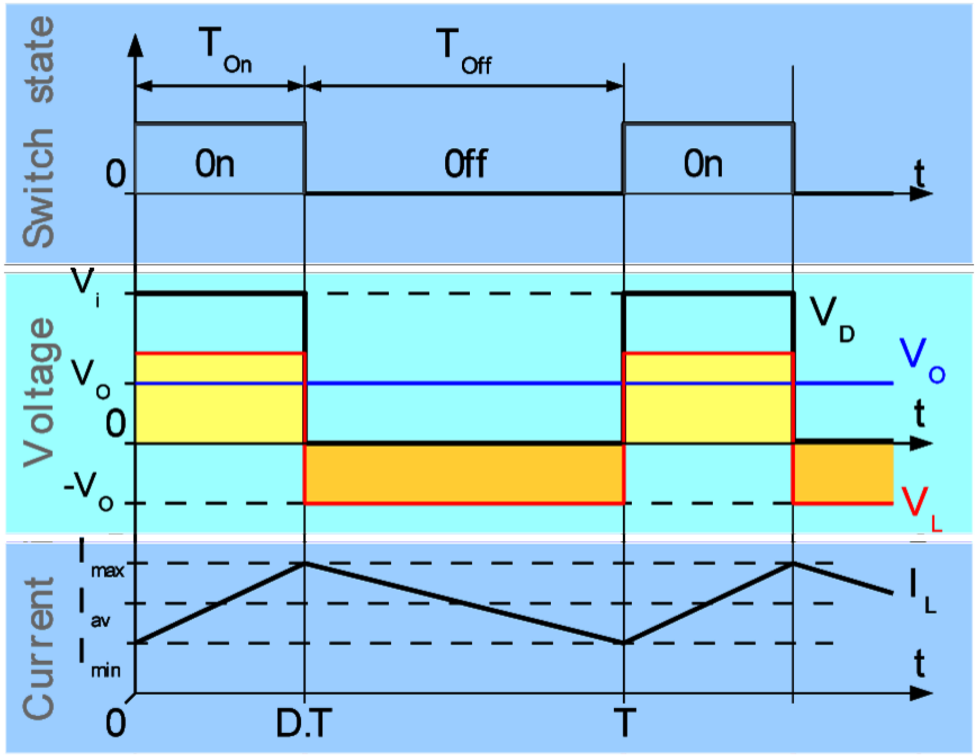



Why? Efficiency ~90%

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

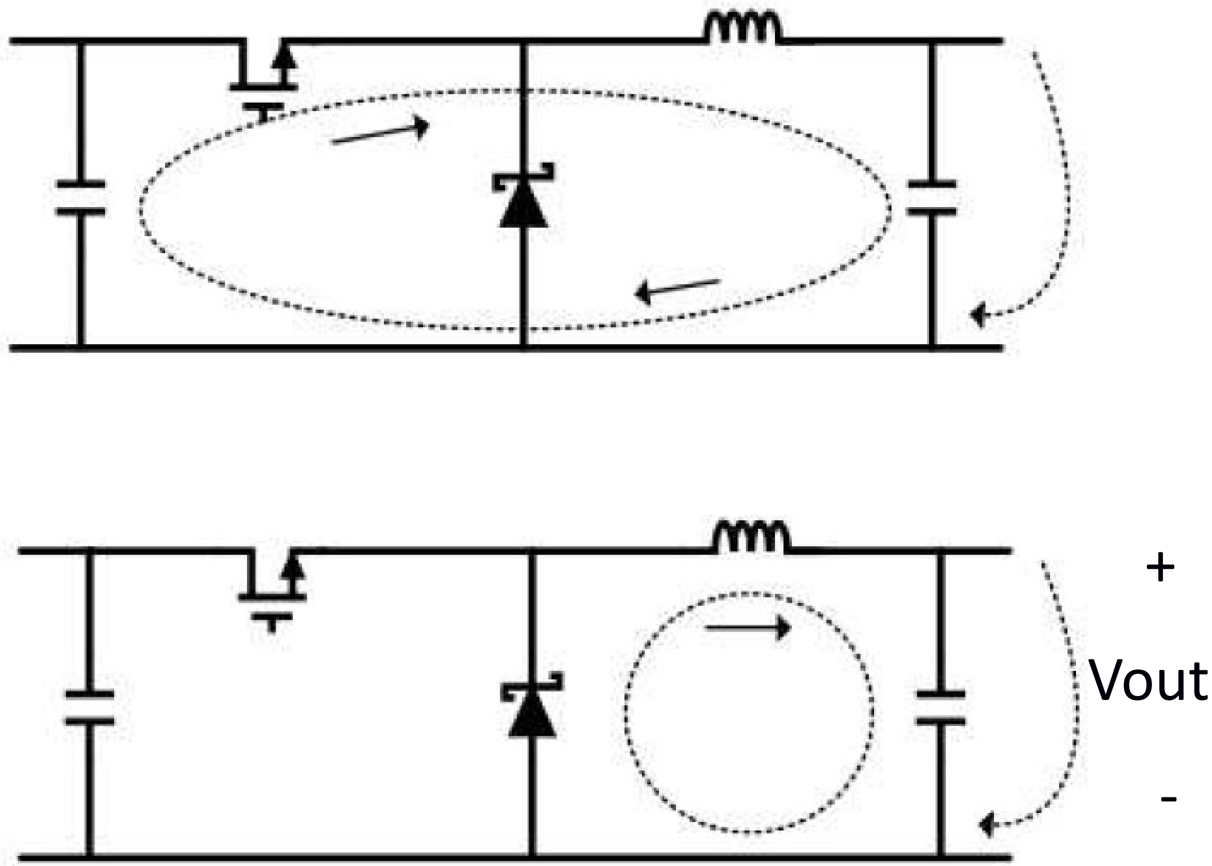
# Buck Converter



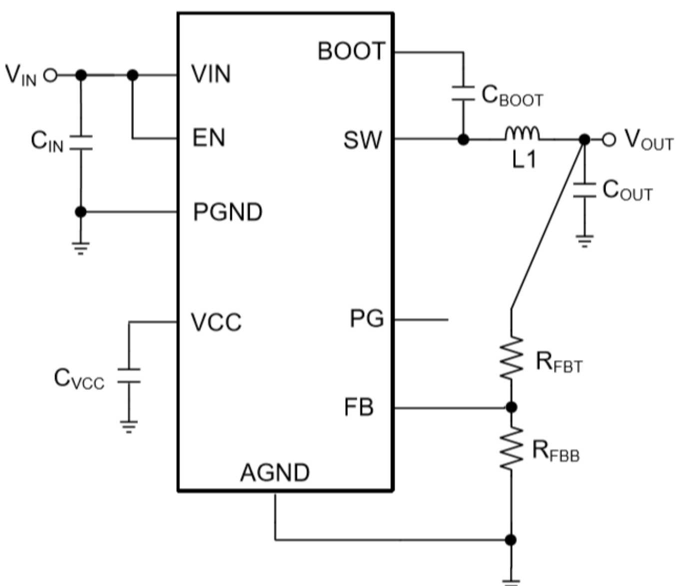



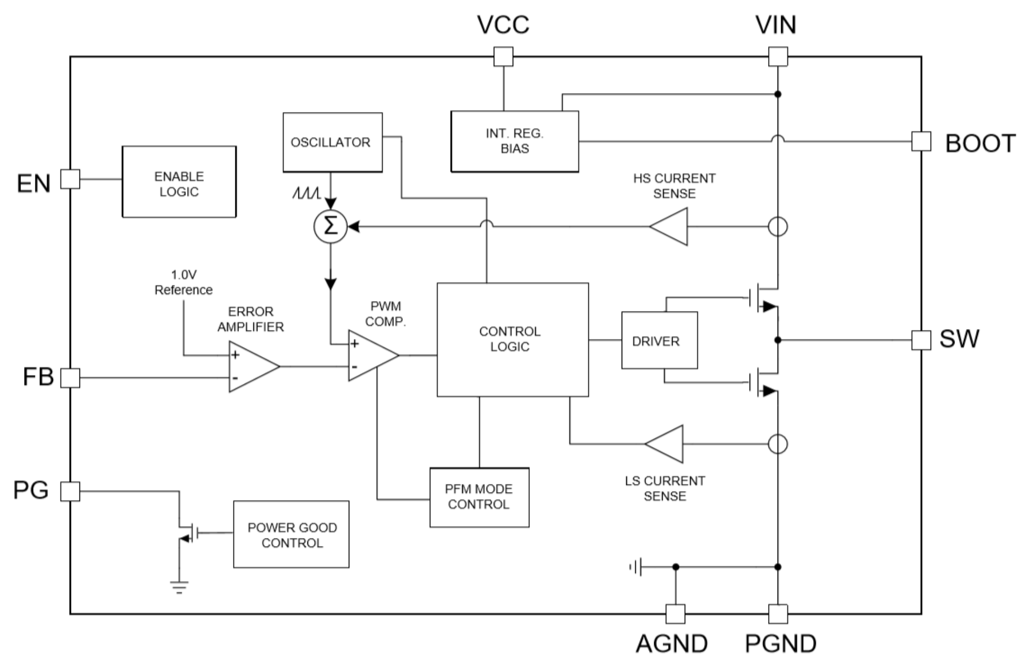

https://en.wikipedia.org/wiki/Buck_converter

# Buck Converter LM2678

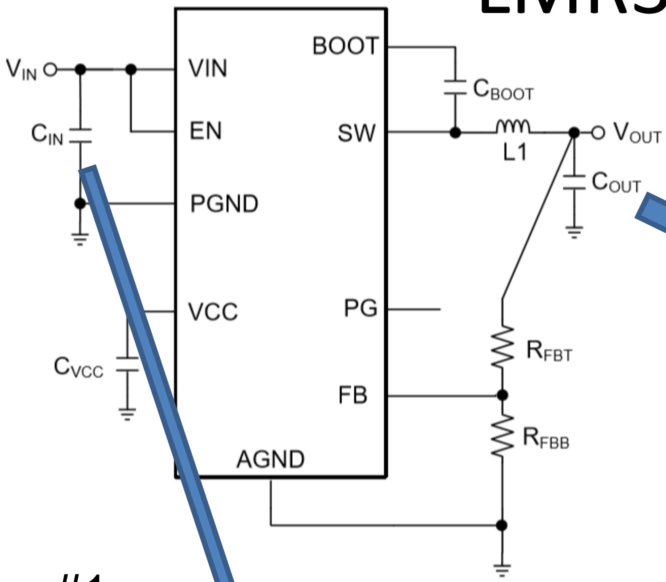


# LMR33630 Buck Converter

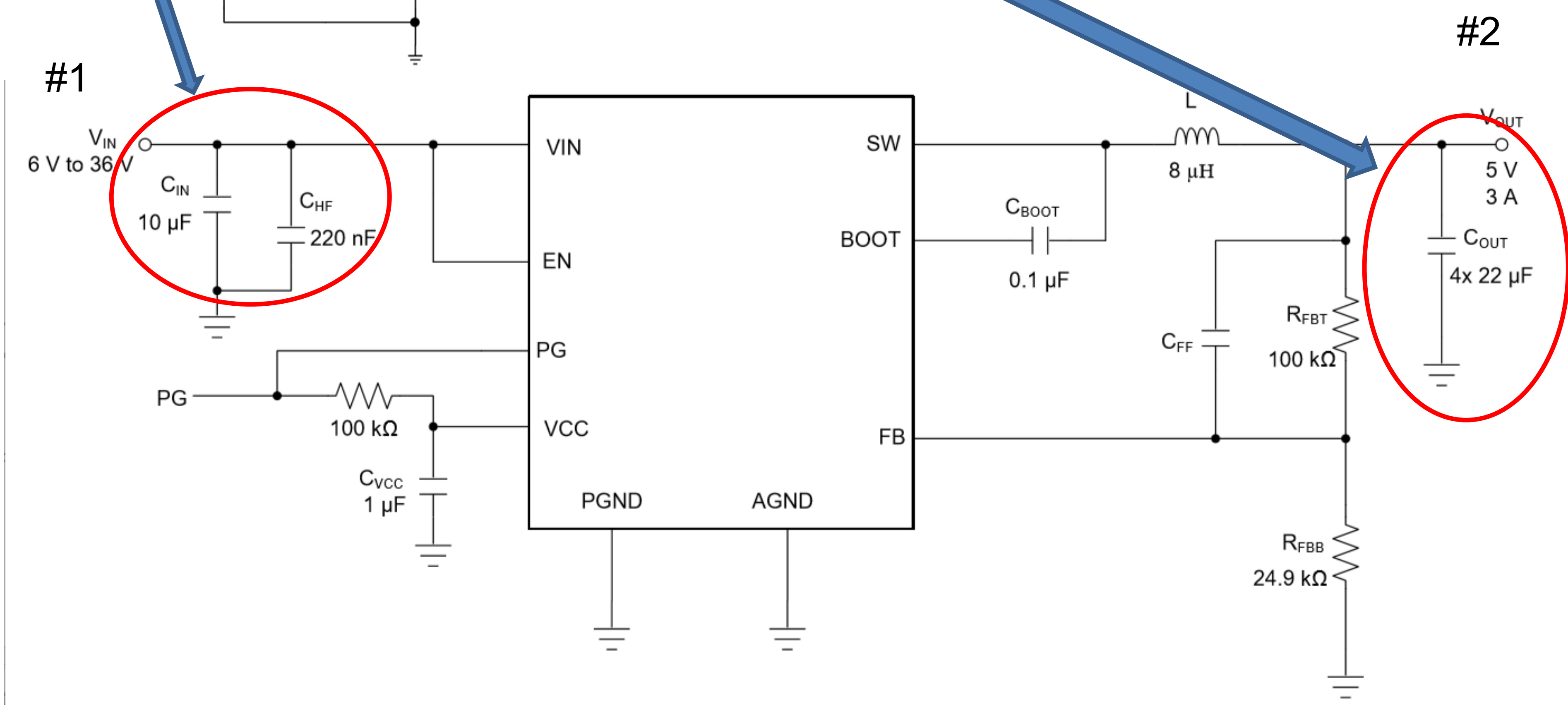


# LMR33630 Buck Converter




… 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.



# Buck Converter Waveforms

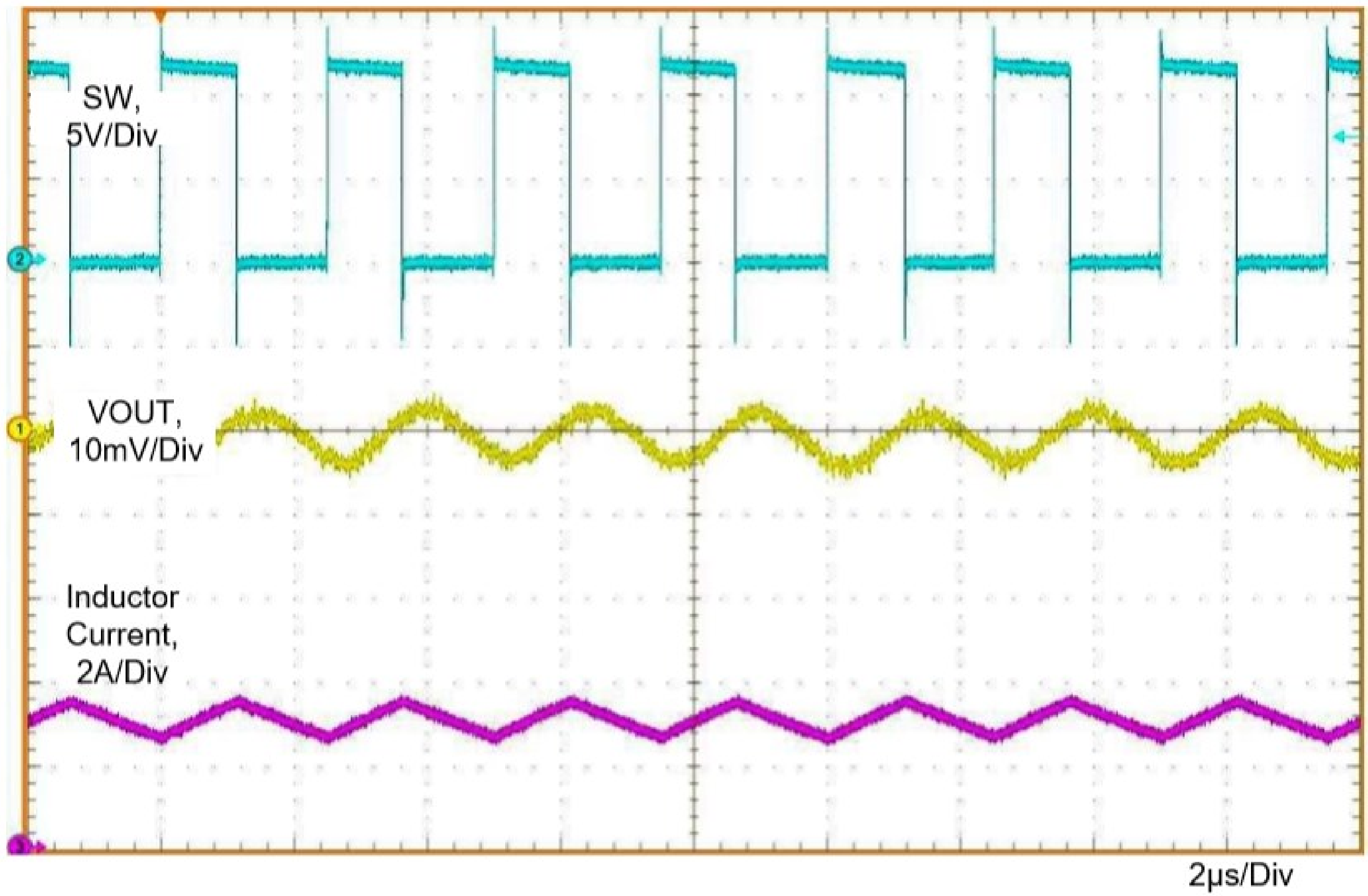



**Figure 14. Typical PWM Switching Waveforms**
**$V_{IN}$ = 12 V, $V_{OUT}$ = 5 V, $I_{OUT}$ = 3 A, $f_S$ = 400 kHz**

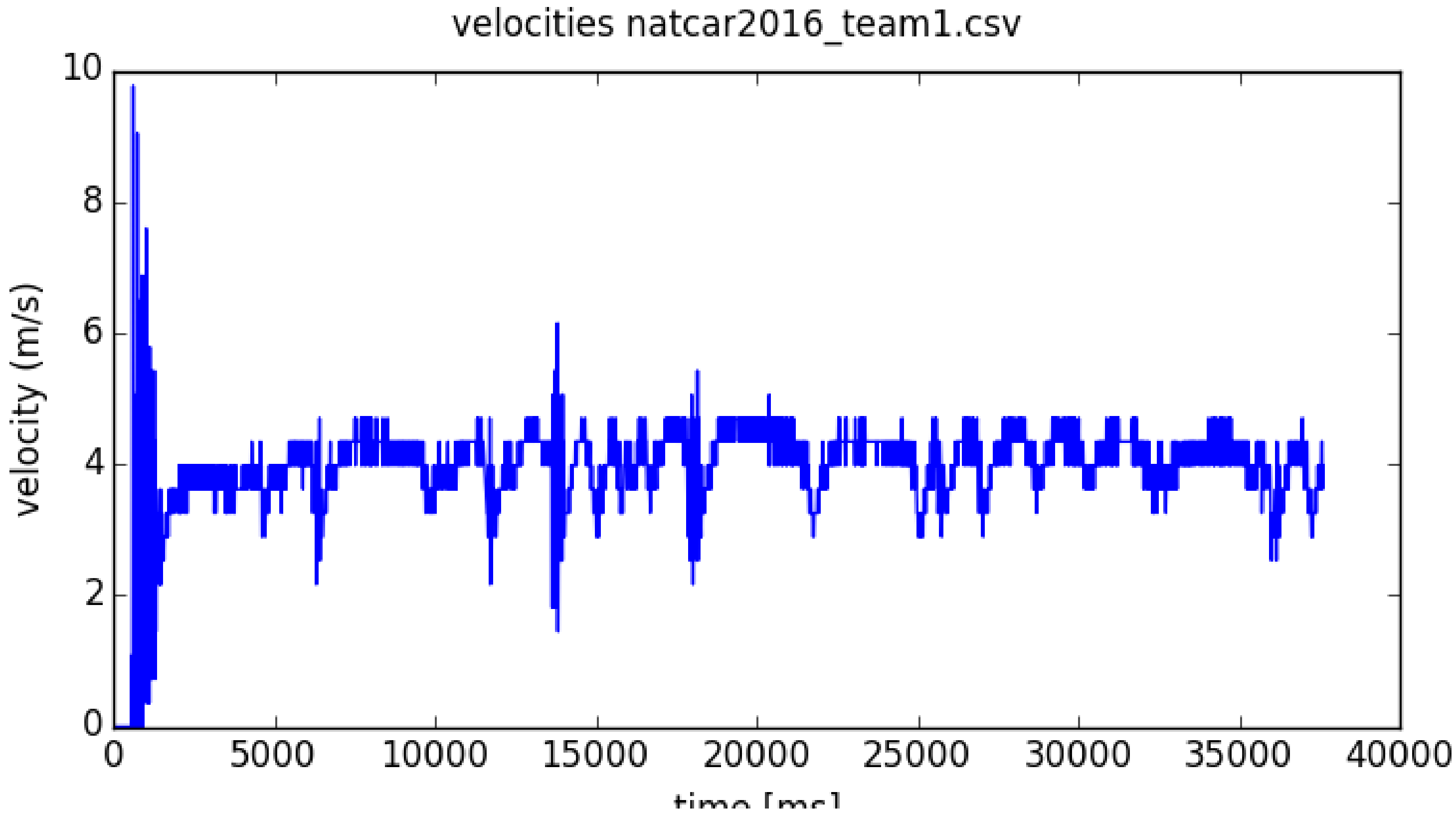
# Extra Slides

# Timing range

```
time_min = rc_nanos_since_boot();
angle1 = rc_encoder_read          ( int  ch);
time_max = rc_nanos_since_boot();
```

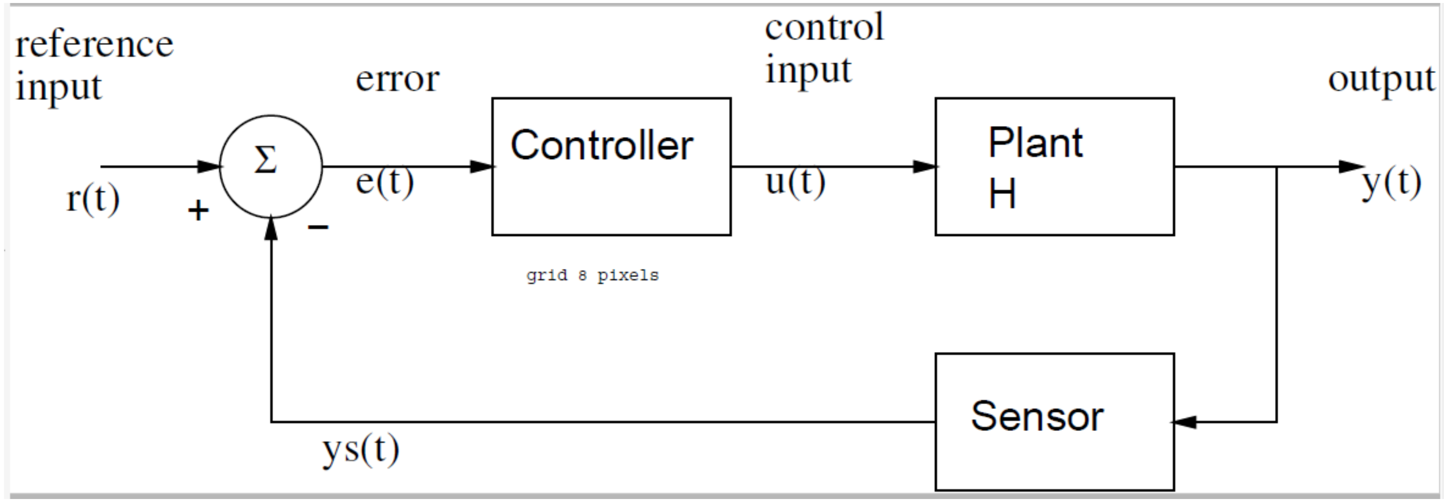
# Velocity Sensing

- On board: estimating $\Delta x / \Delta T$




Note: care about velocity sensing usually at cruise speed (also stopping)

# 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:

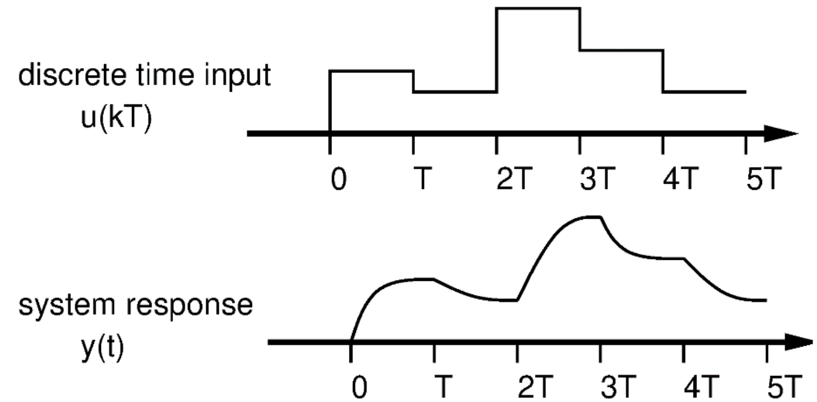
$$x(t_o) = e^{a' t_o} x(0) + \int_0^{t_o} e^{a'(t_o - \tau)} b' r(\tau) d\tau \; . \tag{10}$$

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




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

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

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

# 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:

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

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

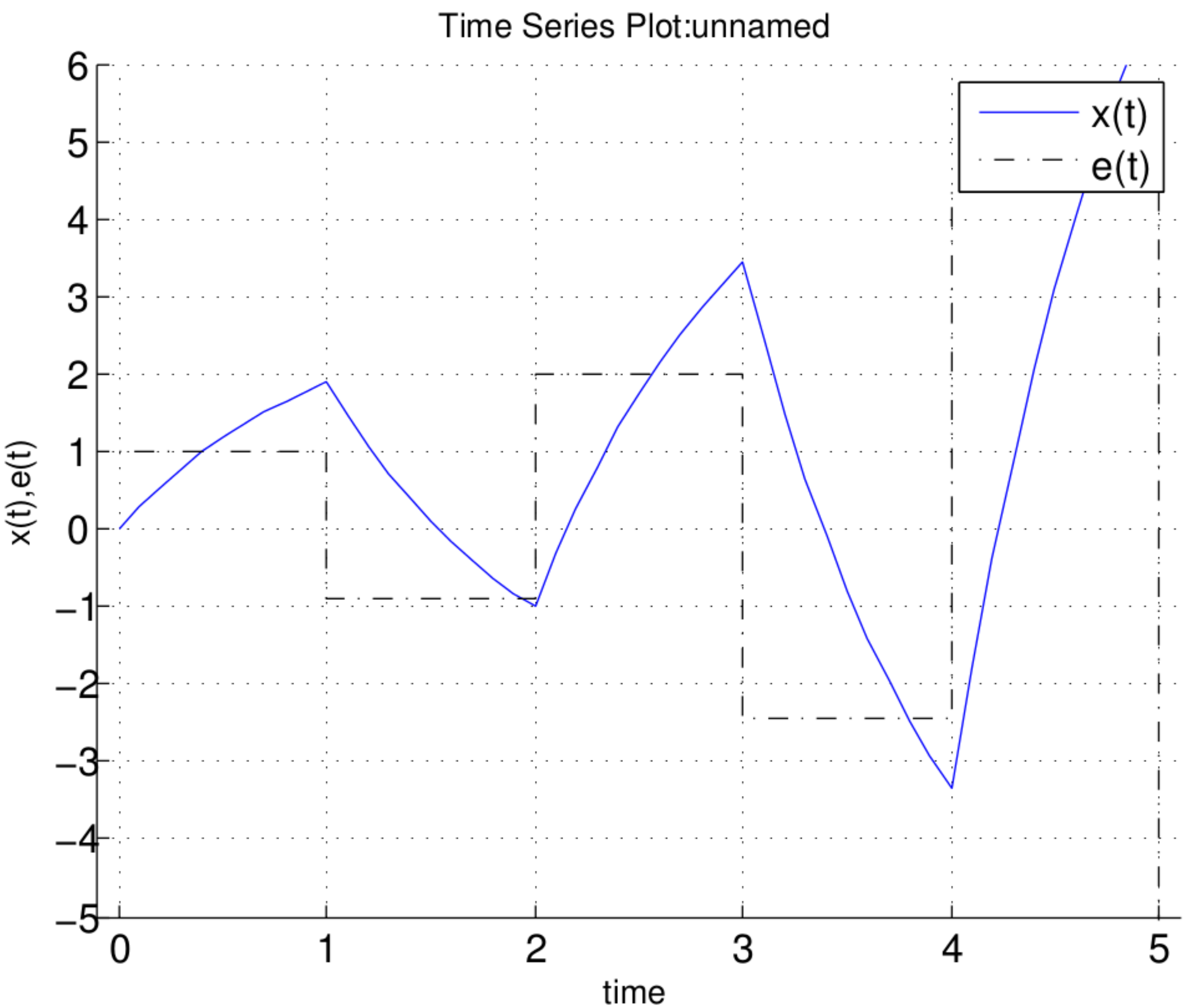
For stability:

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

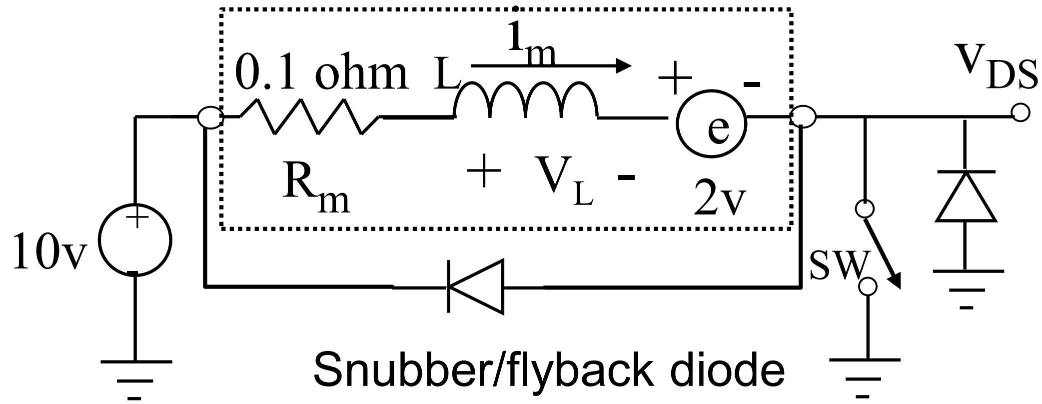
Notes: stability depends on gain **and** T!

# Discrete Time Control

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




On board



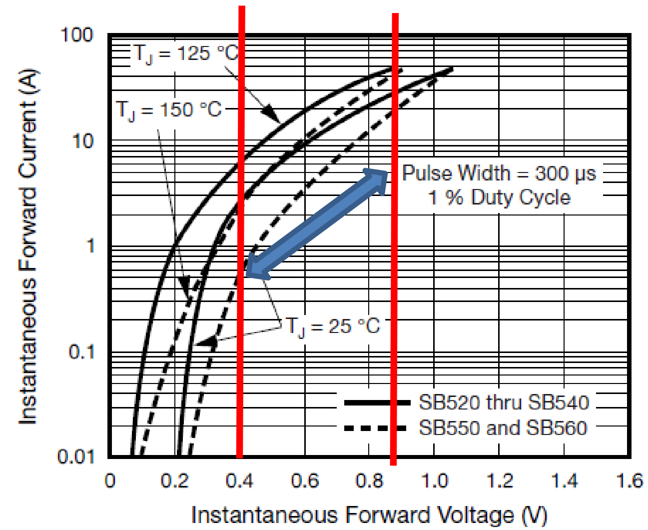
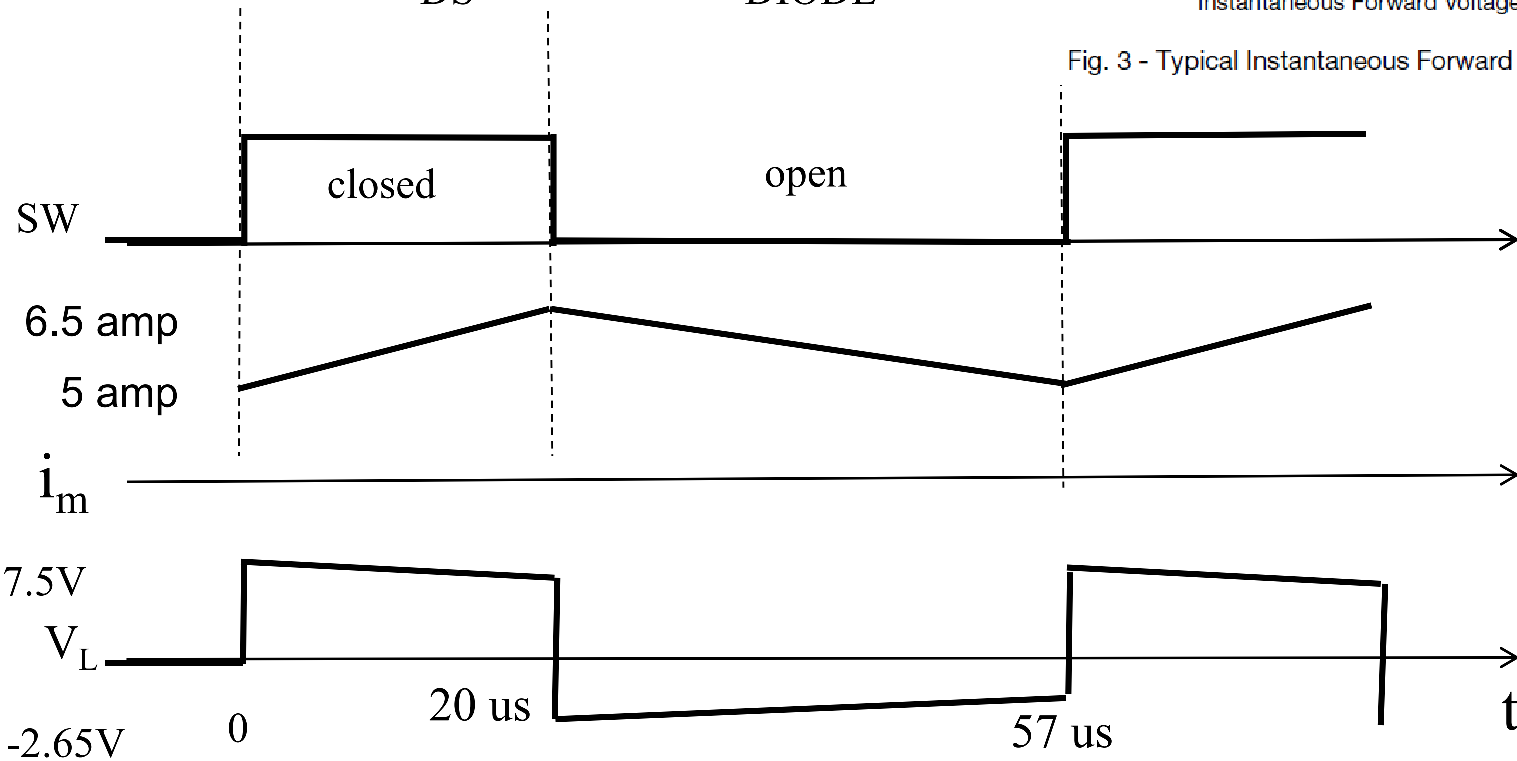




Fig. 3 - Typical Instantaneous Forward Characteristics

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




# Back EMF velocity sensing