EE445M/EE360L.6
Embedded and Real-Time Systems/ Real-Time Operating Systems

Lecture 11:

Robot Design, Teams, Control Systems, PID & Fuzzy Control

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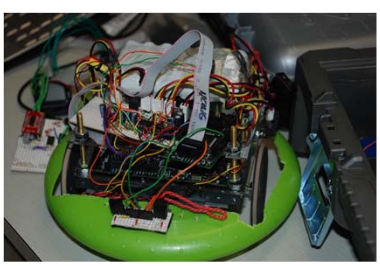
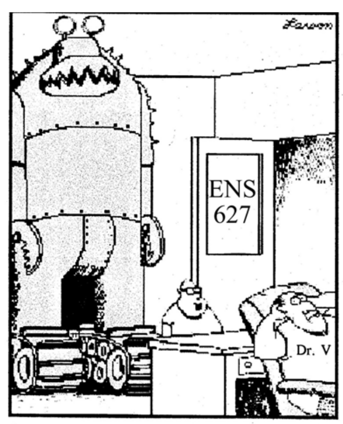
Robot Design

- **Teams**
- **Design process**





"My project's ready for grading, Dr. Big Nose... Hey! ... I'm talking to you, squid brain!"

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What is a team?

"A team is a small number of people with complementary skills who are committed to a common purpose, performance goals, and approach for which they are mutually accountable."

(Katzenbach, J.R. & Smith, D.K. (1993). The Wisdom of Teams: Creating the High-performance Organization. Boston: Harvard Business School.)

Decker, Philip, J. (1996) "Characteristics of an Effective Team," (Powerpoint) http://www.cl.uh.edu/bpa/hadm/HADM_5731/ppt_presentations/29teams

Breslow, L. (1998). Teaching Teamwork Skills, Part 2. Teach Talk, X, 5. http://web.mit.edu/tll/published/teamwork2.htm. 13 May 2003.

Building Blocks for Teams, (Website). Penn State University, http://tlt.its.psu.edu/suggestions/teams/student/index.html

Stages of Team Development

- **Forming**
  - The stage where team members are just becoming acquainted—the "honeymoon"
- **Storming**
  - Conflict begins as team members negotiate work assignments, discuss what to do
- **Norming**
  - Team members learn to work together—pride begins to develop
- **Performing**
  - Team settles down and most of the work gets done

Team Leader Role

- **Responsibilities**:
  - Calling meetings including finding a mutually agreeable time and place
  - Setting a meeting agenda (more on this later)
  - Facilitating the meeting (more later)
  - Monitoring progress against the plan
  - Identifying problem areas that need action
- **Some rules**:
  - The leader is not "the boss"
  - The team needs to agree on decisions and directions
  - Compromise is essential

Holding Effective Meetings

- Before the meeting
  - Name someone to be the facilitator
  - Create an agenda and send it to all team members
- Set a time limit for the meeting
- During the meeting, if issues emerge that are not on the agenda, the facilitator should:
  - Ask the team if this should be discussed now, or
  - Table the issues for the end of the meeting
- During the meeting:
  - Keep a list of decisions and actions items
  - Keep to the time commitment
  - Create an agenda for next meeting and agree on time and place
- After the meeting:
  - Send out a brief summary
  - List of action items
  - Those responsible for those actions

Brainstorming

- Select someone to be the recorder
- Invite everyone to give their ideas and input
- Write down all ideas without criticism or discussion
- After complete list is generated, return for discussion/analysis
- Carefully select the best approach or idea from the list

Brainstorming - Hints for Success

- Avoid being judgmental of others' ideas
- Try to look at all sides of an idea.
- Listen attentively and treat your teammates' opinions with respect
- Try to encourage the widest range of new ideas
- Everyone should participate
- Don't stop the idea session too soon
- Try to remove your ego from the discussions.
- Don't take the rejection of your ideas personally.

Group Communication

- Listen attentively and respect your teammates
- Ask questions
- Give constructive feedback:
  - Present your ideas forcefully, but keep an open mind.
  - Restate the original idea to be sure it's understood
  - Critique the idea, not the person
  - Be courteous
  - Be aware of body language and tone
- Meetings don't need to be a death march
  - Use humor effectively
  - Laugh with someone, do not laugh at someone

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Team Problems (1)

- **Frustration** over the size of the project
  - Members think of an individual endeavor rather than a group endeavor
  - Break the project up into tasks
  - Engage all group members
  - Set realistic dates for each task

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Team Problems (2): Conflict

- **Internal conflict** – An team member is experiencing a personal conflict that is interfering with his or her ability to perform
- **Individual conflict with another team member** - One team member is in conflict with another
- **Individual conflict with the entire team** - One team member is experiencing conflict with the entire team
- **Conflict between several team members** - The entire team is experiencing conflict with several other team members

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Conflict Resolution

- Acknowledge that the conflict exists
- Gain common ground
  - Seek to understand all angles: Let each person state his or her view briefly.
  - Have neutral team members reflect on areas of agreement or disagreement.
  - Explore areas of disagreement for specific issues.
  - Have opponents suggest modifications to their points of view as well as others.
  - If consensus is blocked, ask opponents if they can accept the team's decision.
- Attack the issue, not each other
- Develop an action plan

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An Effective Team Checklist

- Define a common goal for the project
- List tasks to be completed
- Assign responsibility for all tasks
- Develop a timeline and stick to it
- Develop and post a Gantt chart for the plan
- Document key decisions and actions from all team meetings.
- Send reminders when deadlines approach.
- Send confirmation when tasks are completed.
- Collectively review the project output for quality

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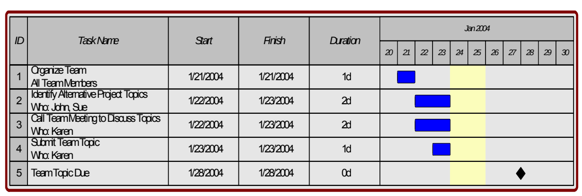
Project Management

- Sensor
- Motor
- Mechanicals
- Network
- Power
- Control
- Debugging

Break project into little tasks
Give yourself some milestones to show success

Gantt Chart



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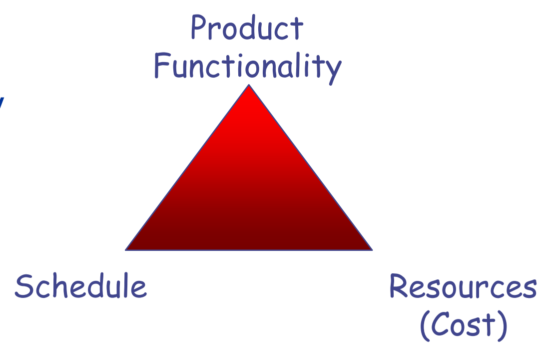
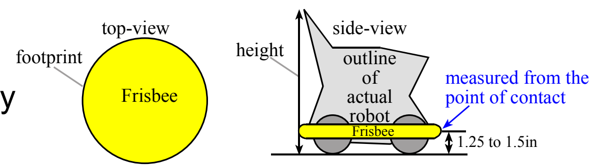
Design Process

- We can only optimize two of the following
  - Schedule
  - Resources
  - Functionality



1) Analysis Phase

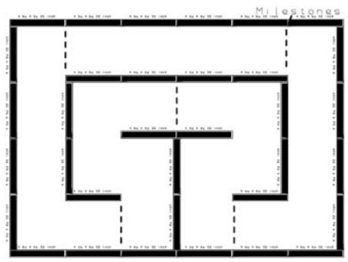
- ***Requirements*** parameters that the system must satisfy
  - Lab 7 rules
- ***Specifications*** describing how the system should work
  - Frisbee
  - Tracks
  - One 8.4V battery
  - Existing motors
  - 3 minute race

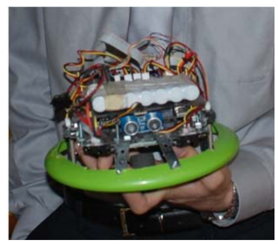


- ***Constraints*** limitations, within the system must operate
  - The kit+$50
  - Play nice with other robots
  - Interfaces with other instruments and test equipment
  - Development schedule

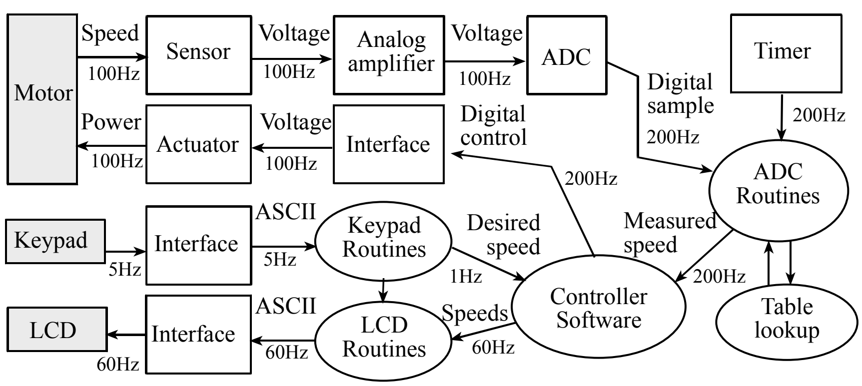
2) High-Level Design Phase

- Project proposal
  - Build conceptual models
    - data flow graph
    - block diagrams
    - fundamental equations
  - Exploit abstraction
  - Search for existing components
  - Try different control algorithms



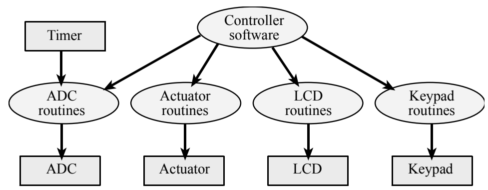


Data Flow Graph

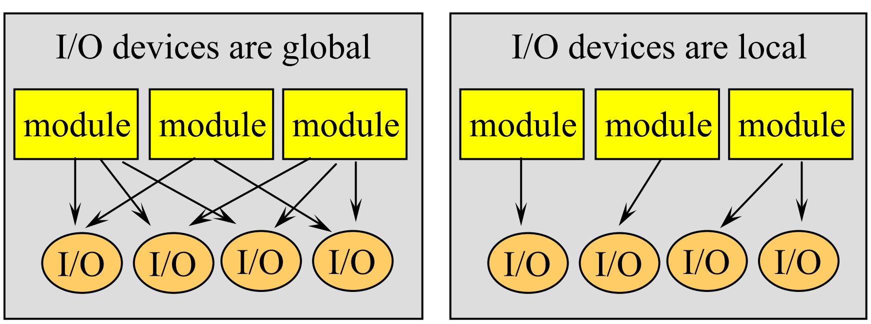


3) Engineering Design Phase

- Hierarchical structure
  - Call-graphs
  - Data structures
  - Flow charts
- Basic I/O interfaces
- Overall software scheme
- Direct correlation between hardware/software systems and conceptual models
- Built mock-ups of the mechanical parts (connectors, chassis, cables etc.)
- Mock-ups of user software interface



Call Graph



4) Implementation Phase

- Concurrent implementation
- Initially implement using simulation
- Divide into modules
- Unit-level testing and debugging

5) Testing Phase

- Design for test
- Concurrent testing
  - Bottom up, from unit-level to subsystem and system integration
- Control and observability
  - Use OLED SDC, UART, …

Race Tracks

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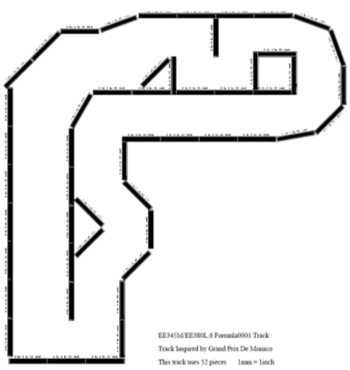
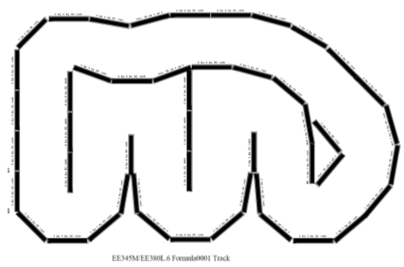
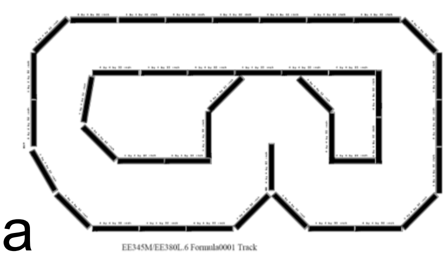
Von Deutschland

Monaco







Espana

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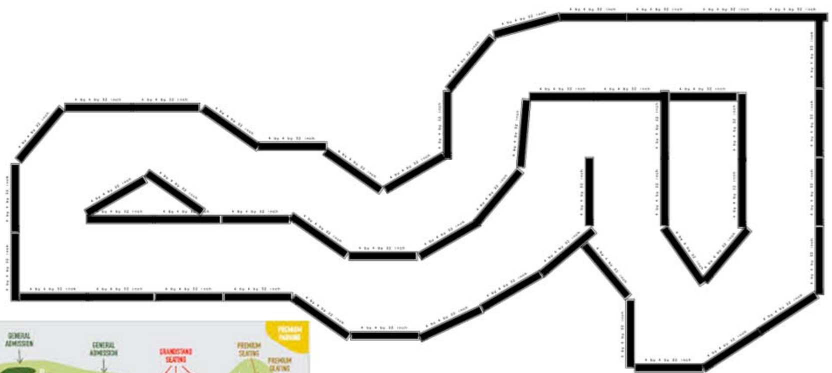
Circuit of the Americas



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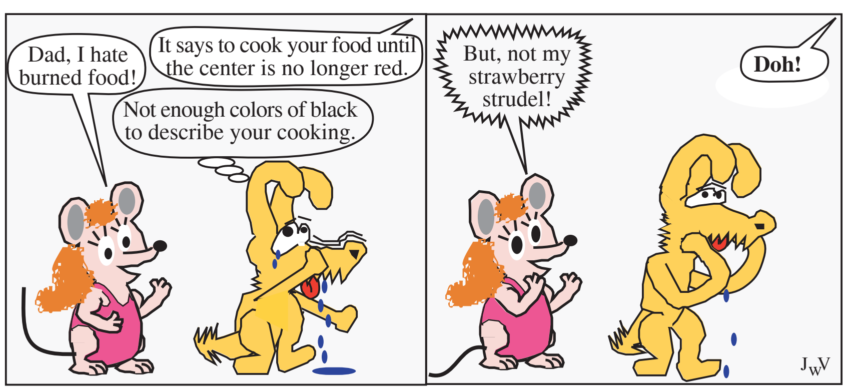
Control Systems

- **Easy: Incremental**
- **Linear: P, PI, PID**
- **Intuitive: Fuzzy Logic**



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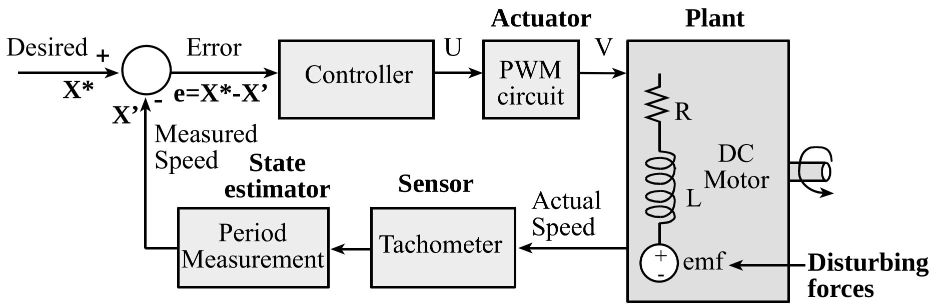
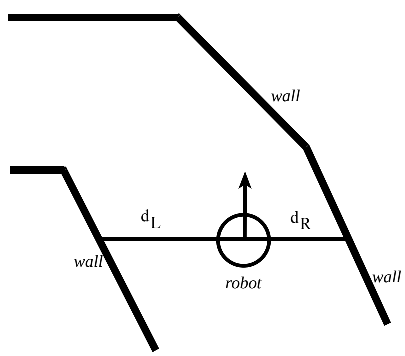
What to Control?

- Motor speed
  - Error = Desired speed – Actual speed
  - Error = Desired period – Actual period



What to Control?

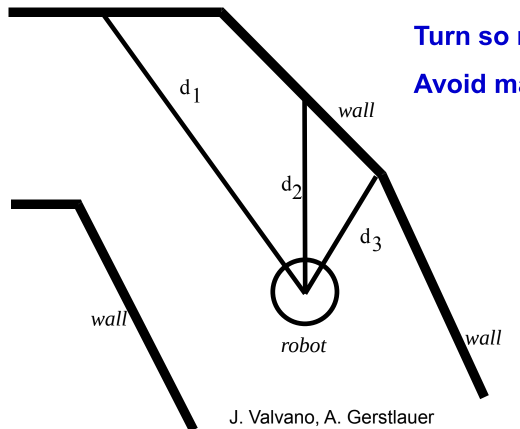
- Distance to one wall
  - Error = Desired distance – Actual distance
- Equal distances to both walls
  - Error = Left distance – Right distance



Sensors
- **Time constant -> f_s**
- **Filters**
  Analog, digital
- **Signal/noise ratio**
- **Calibration**
  accuracy, drift

What to Control?

- Angle to most open track
  - Error = Desired – Actual angle



Turn so most open in front

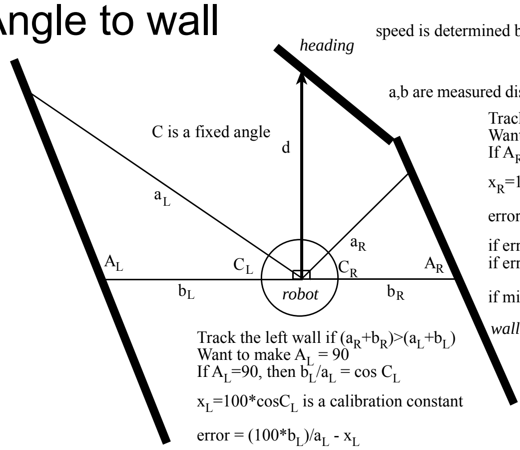
Avoid making U-turns

What to Control?

- Angle to wall

speed is determined by distance,d, to object in front

a,b are measured distances from center of robot to the wall



Track the right wall if $(a_R+b_R)<(a_L+b_L)$
Want to make $A_R = 90$
If $A_R=90$, then $b_R/a_R = \cos C_R$

$x_R=100*\cos C_R$ is a calibration constant

error = $(100*b_R)/a_R - x_R$

if error > 0, $A_R < 90$, turn left
if error < 0, $A_R > 90$, turn right

if $\min(a_R,b_R)<20$, move left-right

Track the left wall if $(a_R+b_R)>(a_L+b_L)$
Want to make $A_L = 90$
If $A_L=90$, then $b_L/a_L = \cos C_L$

$x_L=100*\cos C_L$ is a calibration constant

error = $(100*b_L)/a_L - x_L$

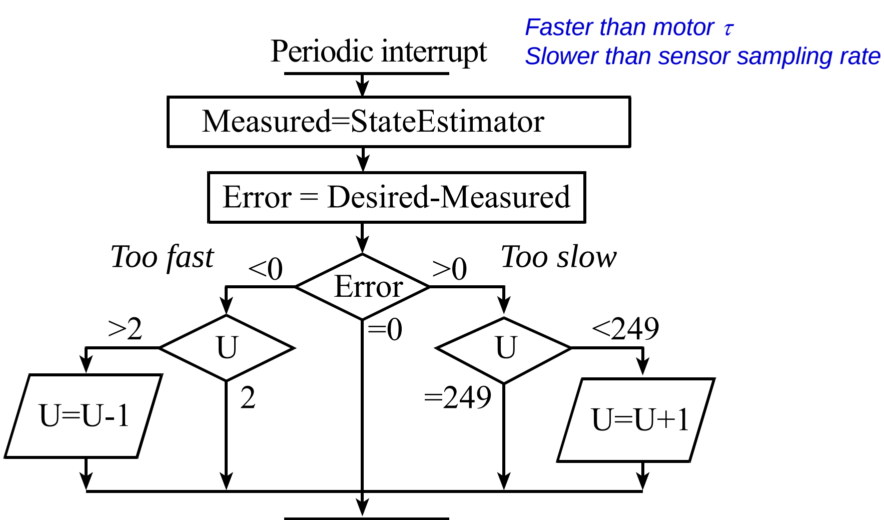
if error > 0, $A_L < 90$, turn right
if error < 0, $A_L > 90$, turn left

if $\min(a_L,b_L)<20$, move right-left

Performance Measures

- Accuracy
  - Magnitude of the Error = Desired– Actual
- Stability
  - No oscillations
- Overshoot (underdamped, overdamped)
  - Ringing, slow
- Response Time to new steady state after
  - Change in desired setpoint
  - Change in load

Incremental Controller



Incremental Controller

```
long Xstar; // desired
long X;     // actual, measured input
long U;     // PWM actuator output
void Timer0A_Handler(void){ long E;
  E = Xstar-X;         // error
  if(E < 0)      U--;  // too fast
  else if(E > 1) U++;  // too slow
                       // close enough
  if(U <   2) U=2;    // Constrain output
  if(U > 249) U=249;
  PWM0_Duty(U);         // output
  TIMER0_ICR_R = TIMER_ICR_CAECINT;
}
```

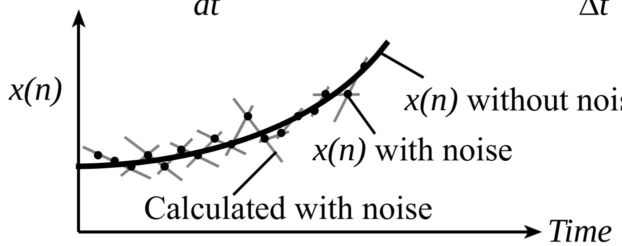

PID Controller

$$U(t) = K_p E(t) + \int_0^t K_i E(\tau) d\tau + K_d \frac{dE(t)}{dt}$$

- Proportional $U_p = K_p E$
- Integral $U_i = U_i + K_i E \Delta t$
- Derivative $U_d = K_d(E(n)-E(n-1))/\Delta t$
- PID $U = U_p + U_i + U_d$
- Run ten times faster than motor τ
- Run slower or equal to sensor sampling rate

Derivative Term

$$D(t) = K_d \frac{dE(t)}{dt} \quad \Rightarrow \quad D(n) = K_d \frac{E(n) - E(n-1)}{\Delta t}$$



$$D(n) = K_d\left(\frac{1}{2}\frac{E(n)-E(n-3)}{3\Delta t} + \frac{1}{2}\frac{E(n-1)-E(n-2)}{\Delta t}\right)$$

$$D(n) = K_d\left(\frac{E(n)+3E(n-1)-3E(n-2)-E(n-3)}{6\Delta t}\right)$$

- **Analog filter**
- **Digital filter**
- **Linear regression**

PI Controller

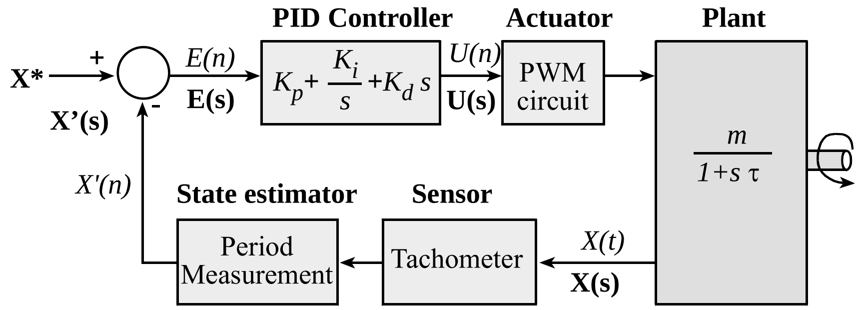
```
void Timer0A_Handler(void){
  E = Xstar-X;
  P = (105*E)/20;      // Kp = 105/20
  I = I+(101*E)/640;   // KiΔt = 101/640
  if(I < -500) I=-500; // anti-reset windup
  if(I > 4000) I=4000;
  U = P+I;             // PI controller
  if(U < 100) U=100;   // Constrain output
  if(U>19900) U=19900;
  PWM0_Duty(U);        // output
  TIMER0_ICR_R = TIMER_ICR_CAECINT;
}
```

Laplace Domain

$$G(s) = K_p + K_d s + \frac{K_i}{s}$$

$$H(s) = \frac{m}{1+\tau\, s}$$

$$\frac{X(s)}{X^*(s)} = \frac{G(s)H(s)}{1+G(s)H(s)}$$



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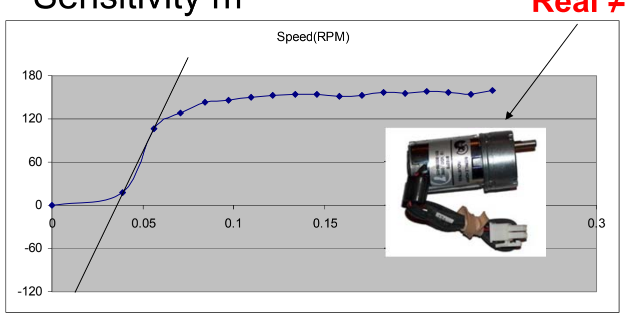
Motor Parameters

- Invoke a step, measure response
  - Time lag, time constant, τ
- Plot speed in RPM versus duty cycle
  - Sensitivity m

Real ≠ Theory



$$H(s) = \frac{m}{1+\tau\, s}$$

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Controller Tuning

- Start with just a proportional term (**Kp**)
  - proportional controller will generate a smooth motor speed
  - choose the sign of the term Kp so the system is stable
  - try different Kp constants until the response times are fast enough
- The next step is to add some integral term (**Ki**)
  - a little at a time
  - to improve the steady state controller accuracy
  - without adversely affecting the response time
  - choose the sign of the term Ki so the system is stable
  - Don't change both Kp and Ki at once.
- The last step is the derivative term (**Kd**)
  - a little at a time
  - reduce the overshoots/undershoots in the step response
  - choose the sign of the term Kd so the overshoots/undershoots are reduced

Highly nonlinear -> empirical approach

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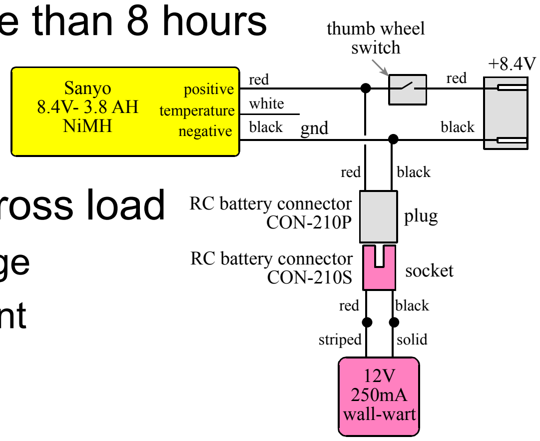
Charging Battery

- Drain battery 10Ω 25W resistor (or motor)
- Charge no more than 8 hours
- Test battery across load
  - Measure voltage
  - Measure current
  - 3.8 Amp-hour



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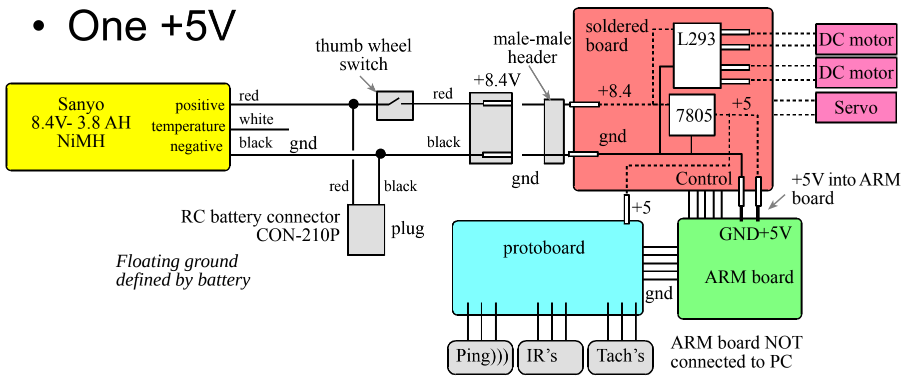
Under Battery Power

- Current path battery-motor-battery
- Ground
- One +5V



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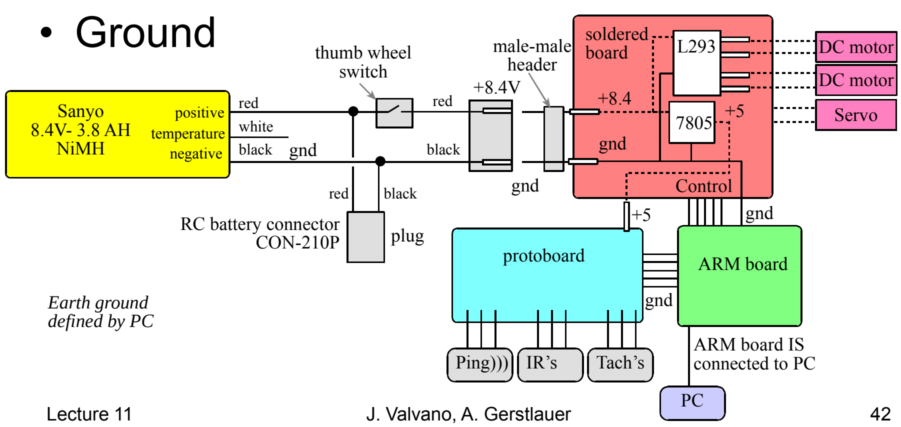
While Debugging with PC

- Prevent motor current from going to board
- Two +5V, not connected
- Ground



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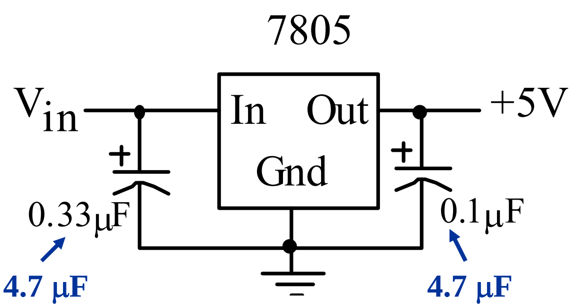
Regulator

- Drop out, V_d
- Calculate power loss, P=(8.4-5)*I



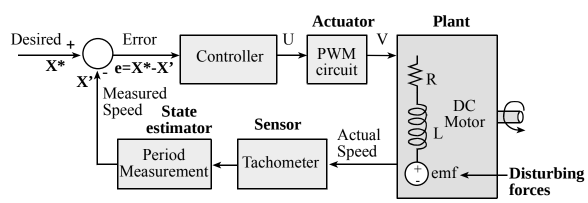
$V_d = 2.5V$

$V_{in} > 7.5V$

$I_{out} < 1A$

Fuzzy Logic Controller

- Incremental
  - + Simple, stable
  - - Slow response



- PID or PI
  - + Theory, fast response
  - - Needs empirical tuning, depends on load
- Fuzzy Logic Maps human intuition into rules
  - + Fast, good when you have expert knowledge
  - + Abstractive approach
  - - Needs empirical tuning

Fuzzy Membership Set

- Membership set, variable, set
  - Value specifying levels of truth
  - Collection describes the entire system

0........32........64.........96.........128........160........192........224........255
Not at all...a little bit...somewhat...mostly...pretty much...definitely

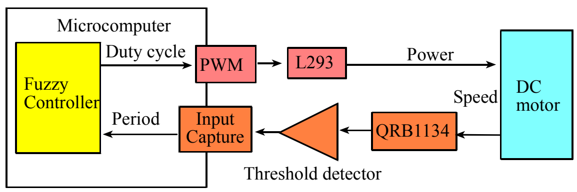
- Examples for a speed control system
  - TooSlow
  - SpeedOK
  - TooFast
  - SlowingDown
  - SpeedConstant
  - SpeedingUp

Fuzzy Membership Set

- Lab 7 example membership sets
  - Too close to the right wall
  - Distance to the right wall is ok
  - Too far away from the right wall
  - Too close to the left wall
  - Distance to the left wall is ok
  - Too far away from the left wall
  - Open space to 30 degrees to the right
  - Open space to straight ahead
  - Open space to 30 degrees to the left

Speed Controller

- Desired state
  - X* is the desired tach period
- Physical plant
  - X real state variable, actual period
- State estimator, data acquisition
  - X' measured tach period



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Fuzzy Approach

- Preprocessor
  - Crisp inputs (variables with units)
- Fuzzification
  - Input membership sets
- Fuzzy rules
  - Output membership sets
- Defuzzification
  - Crisp outputs (variables with units)
- Postprocessor and actuator output

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Preprocessor

- Crisp inputs
  - E = X*-X’ error in motor period
  - D = X’(n) – X’(n-1) acceleration

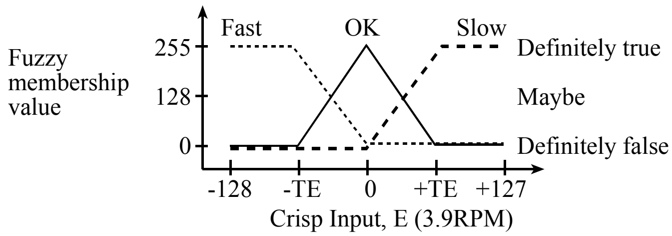
```
unsigned char Ts;     // Desired Speed in 3.9 rpm units
unsigned char T;      // Current Speed in 3.9 rpm units
unsigned char Told;   // Previous Speed in 3.9 rpm units
char D;               // Change in Speed in 3.9 rpm/time units
char E;               // Error in Speed in 3.9 rpm units
void CrispInput(void){
     E=Subtract(Ts,T);
     D=Subtract(T,Told);
     Told=T;     /* Set up Told for next time */
}
```

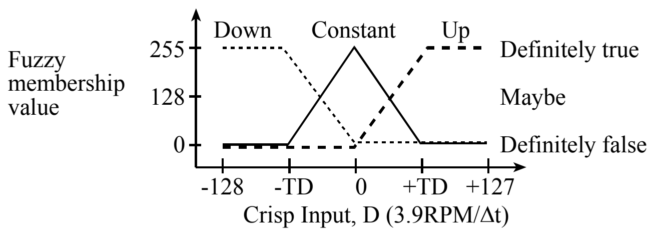

Fuzzification

- Preprocessor, crisp inputs
  - E = X*-X’ error in motor period
  - D = X’(n) – X’(n-1) acceleration
- Fuzzification

Slow	True if the motor is spinning too slow
OK	True if the motor is spinning at the proper speed
Fast	True if the motor is spinning too fast
Up	True if the motor speed is getting larger
Constant	True if the motor speed is remaining the same
Down	True if the motor speed is getting smaller.

Fuzzification





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Fuzzification

```
#define TE ???
long Fast, OK, Slow, Down, Constant, Up;
#define TD ???
long Increase,Same,Decrease;
#define TN ???
void InputMembership(void){
  if(E <= -TE) {        /*  E <= -TE */
    Slow = 255;
    OK = 0;
    Fast = 0;}
  else
    if (E < 0) {        /* -TE<E<0 */
      Slow = (255*(-E))/TE;
      OK = 255-Slow;
      Fast = 0;}
    else
      if (E < TE) {     /*  0<E<TE */
        Slow = 0;
        Fast =(255*E)/TE;
        OK = 255-Fast;}
      else {            /* +TE <= E */
        Slow = 0;
        OK = 0;
        Fast = 255;
     }
  if(D <= -TD) {     /* D <= -TD  */
    Up = 255;
    Constant = 0;
    Down = 0;}
  else
    if (D < 0) {    /* -TD<D<0   */
      Up = (255*(-D))/TD;
      Constant = 255-Up;
      Down = 0;}
    else
      if (D < TD) { /*  0<D<TD   */
        Up = 0;
        Down = (255*D)/TD;
        Constant = 255- Down;}
     else {          /* +TD <= D   */
        Up = 0;
        Constant = 0;
        Down = 255;
   }
}
```

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Fuzzy Rules

E \ D	*Down*	*Constant*	*Up*
Slow	*Increase*	*Increase*	
OK	*Increase*	*Same*	*Decrease*
Fast		*Decrease*	*Decrease*

If *OK* and *Constant* then *Same*
If *OK* and *Up* then *Decrease*
If *Fast* and *Constant* then *Decrease*
If *Fast* and *Up* then *Decrease*
If *OK* and *Down* then *Increase*
If *Slow* and *Constant* then *Increase*
If *Slow* and *Down* then *Increase*

Fuzzy Rules

Same=(*OK* and *Constant*)
Decrease=(OK and *Up*) or (*Fast* and *Constant*) or (*Fast* and *Up*)
Increase=(*OK* and *Down*) or (*Slow* and *Constant*) or (*Slow* and *Down*)

- **and** operation is minimum

```
unsigned char static min(unsigned char u1,unsigned char u2){
     if(u1>u2) return(u2);
     else return(u1);
}
```

- **or** operation is the maximum

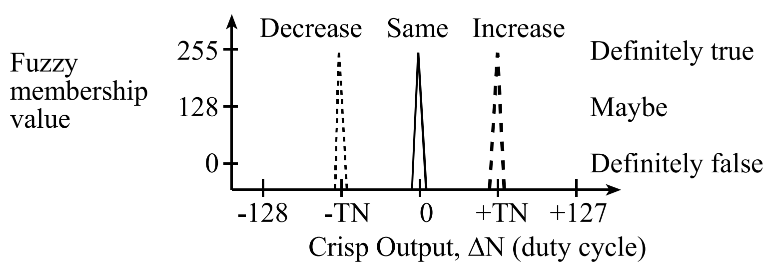
```
unsigned char static max(unsigned char u1,unsigned char u2){
     if(u1<u2) return(u2);
     else return(u1);
}
```

Fuzzy Rules

E \ D	*Down*	*Constant*	*Up*
Slow	*Increase*	*Increase*	
OK	*Increase*	*Same*	*Decrease*
Fast		*Decrease*	*Decrease*

```
void OutputMembership(void){
     Same=min(OK,Constant);
     Decrease=min(OK,Up)
     Decrease=max(Decrease,min(Fast,Constant));
     Decrease=max(Decrease,min(Fast,Up));
     Increase=min(OK,Down)
     Increase=max(Increase,min(Slow,Constant));
     Increase=max(Increase,min(Slow,Down));
}
```


Defuzzification



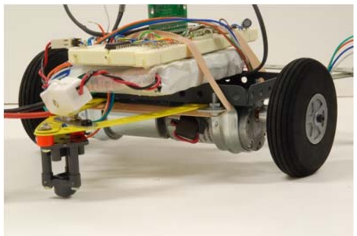
$$\Delta N=(Decrease\cdot(-TN) + Same\cdot 0 + Increase\cdot TN)/(Decrease+Same+Increase)$$

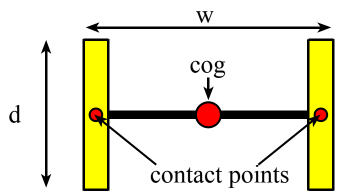
```
long dN;
void CrispOutput(void){
  dN=(TN*(Increase-Decrease))/(Decrease+Same+Increase);
}
```

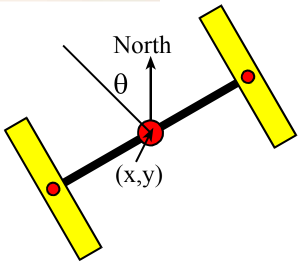
Fuzzy Logic Controller

```
void Timer0A_Handler(void){
  T = SE();                // estimate speed, set T, 0 to 255
  CrispInput();            // Calculate E,D and new Told
  InputMembership();       // Sets Fast,OK,Slow,Down,Constant,Up
  OutputMembership();      // Sets Increase,Same,Decrease
  CrispOutput();           // Sets dN
  N = max(0,min(N+dN,255));
  PWM0_Duty(N);            // output to actuator, Program 8.4
  TIMER0_ICR_R = TIMER_ICR_CAECINT;// ack
}
```


Odometry

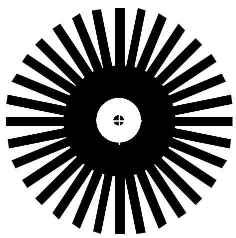


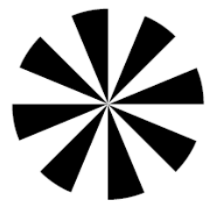




Constants

- Number of slots/rotation, n=32
- Wheel diameter, d=886 (0.01cm)
- Wheelbase, w=1651 (0.01cm)
- Wheel circumference, c=πd=2783 (0.01 cm)





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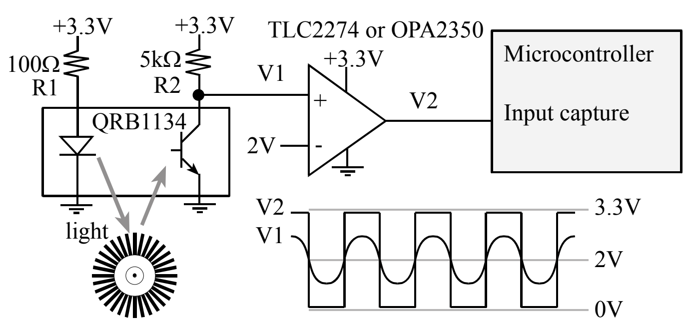
Measurements

- LCount the number of left slots in Δt
- RCount the number of right slots in Δt
- Counts vary from -28 to +28 each Δt



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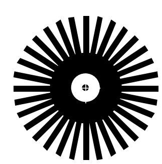
Simple Cases

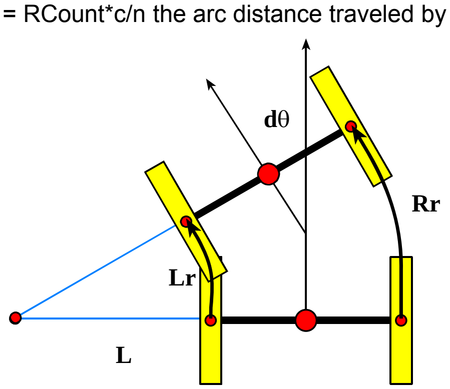
- $-28 \le m \le +28$ each Δt

LCount	*RCount*	*Motion*
m	m	straight line motion in the current direction
0	m	pivot about stopped left motor
m	0	pivot about stopped right motor
m	-m	pure rotation about cog

Derivations



c = circumference
n = number of slots per rotation
w = wheelbase
Lr = LCount*c/n the arc distance traveled by the left wheel (0.01cm)
Rr = RCount*c/n the arc distance traveled by the right wheel (0.01cm)

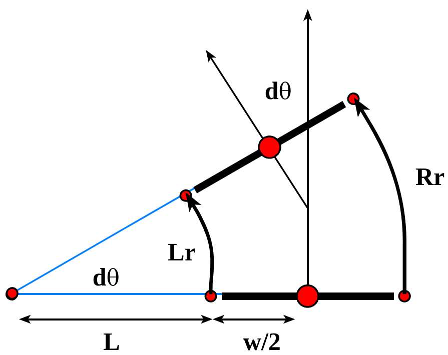


Assume Lr, Rr positive
Assume Rr>Lr

$L/Lr = (L+w)/Rr$
$L/Lr - L/Rr = w/Rr$
$L\,Rr - L\,Lr = w\,Lr$
$L = w\,Lr/(Rr - Lr)$

Derivations

dθ = Lr/L = Rr/(L+w)



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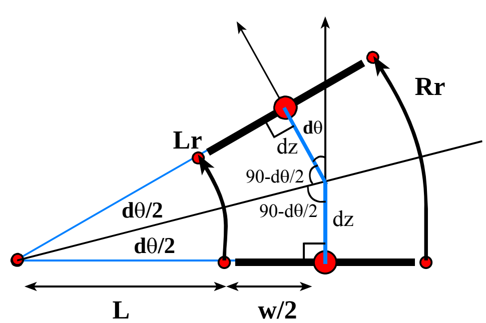
Derivations

We can divide the change in position into two components



dz = (L+w/2)*tan(dθ/2)

if dθ is small

dz = dθ/2*(L+w/2)

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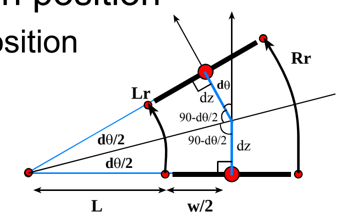
Odometry

- Needs very accurate sensors
  - Errors accumulate
- OK for relative travel from known position
  - periodic absolute knowledge of position



Lr = LCount*c/n	(0.01cm)
Rr = RCount*c/n	(0.01cm)
L = (w*Lr)/(Rr - Lr)	(0.01cm)
dθ = (100*Lr)/L	(0.01 radians)
dz = ((dθ/2)*(L+w/2))/100	(0.01cm) *approximation*
x = x + dz*cos(θ)	(0.01cm)
y = y+ dz*sin(θ)	(0.01cm) *first part of move*
θ = θ + dθ	(0.01 radians)
x = x + dz*cos(θ)	(0.01cm)
y = y+ dz*sin(θ)	(0.01cm) *second part of move*

Things that can go bad

- Hitting the wall
  - Think of three ways to tell if you hit the wall
  - Corrective measures
- Wrong-way Dayo
  - Think of ways to reduce the chances
  - Three repairs -> disqualification
- Other robots in the way
  - Can you distinguish a robot from a wall?
  - Strategy for passing