

ECE445M/ECE380L.12 Embedded and Real-Time Systems/ Real-Time Operating Systems

Lecture 10: Robot Design, Teams, Control Systems, Control Algorithms

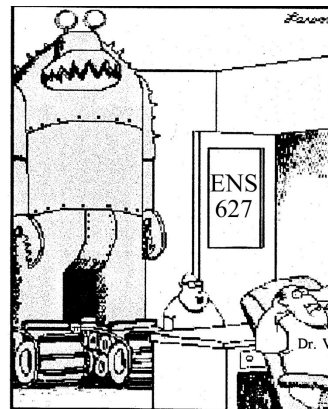
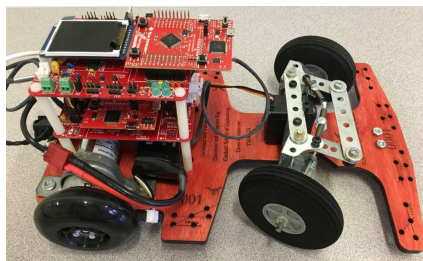
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1

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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2

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>

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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

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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

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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

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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

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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.

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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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9

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

ID	Task Name	Start	Finish	Duration	Jan 2004						
					20	21	22	23	24	25	26
1	Organize Team All Team Members	1/21/2004	1/21/2004	1d							
2	Identify Alternative Project Topics Who: John, Sue	1/22/2004	1/23/2004	2d							
3	Call Team Meeting to Discuss Topics Who: Karen	1/23/2004	1/23/2004	2d							
4	Submit Team Topic Who: Karen	1/23/2004	1/23/2004	1d							
5	Team Topic Due	1/29/2004	1/29/2004	0d							◆

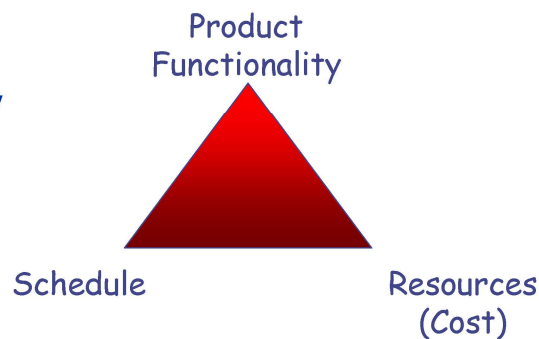
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Design Process

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



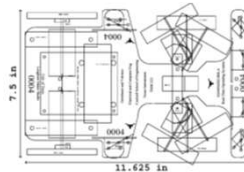
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15

1) Analysis Phase

- **Requirements** parameters that the system must satisfy
 - Lab 7 rules
- **Specifications** describing how the system should work
 - Robot platform
 - Tracks
 - One 11.1V battery
 - Existing motors
 - 3 minute race
- **Constraints** limitations, within the system must operate
 - The platform+\$50
 - Play nice with other robots
 - Interfaces with other instruments and test equipment
 - Development schedule



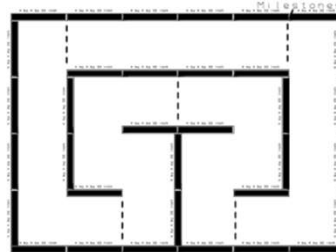
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16

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

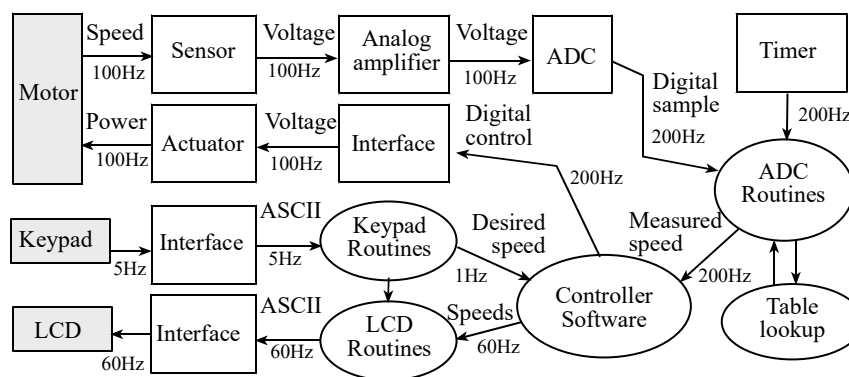


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17

Data Flow Graph



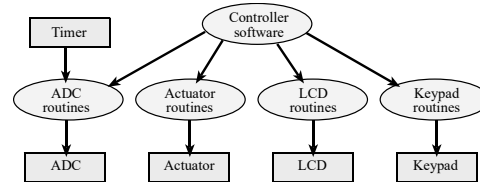
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18

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

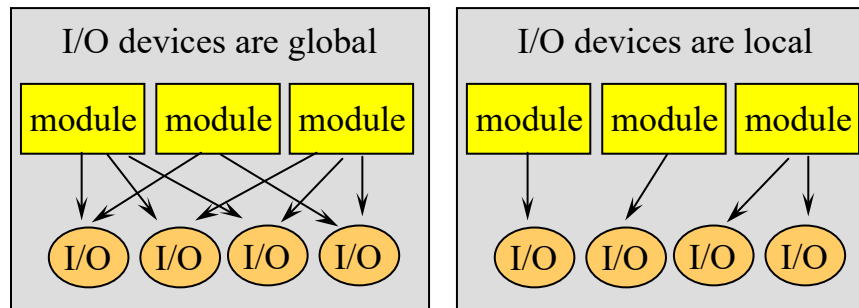


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Call Graph



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20

4) Implementation Phase

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

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21

5) Testing Phase

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

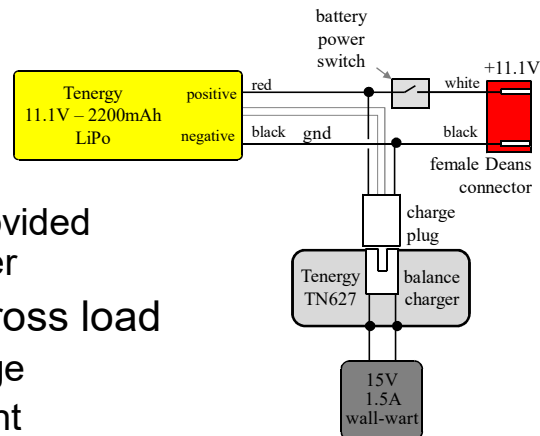
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22

LiPo Battery

- No built-in protection circuit module (PCM)
- Discharging
 - Avoid over-discharge
- Charging
 - Always use provided balance charger
- Test battery across load
 - Measure voltage
 - Measure current



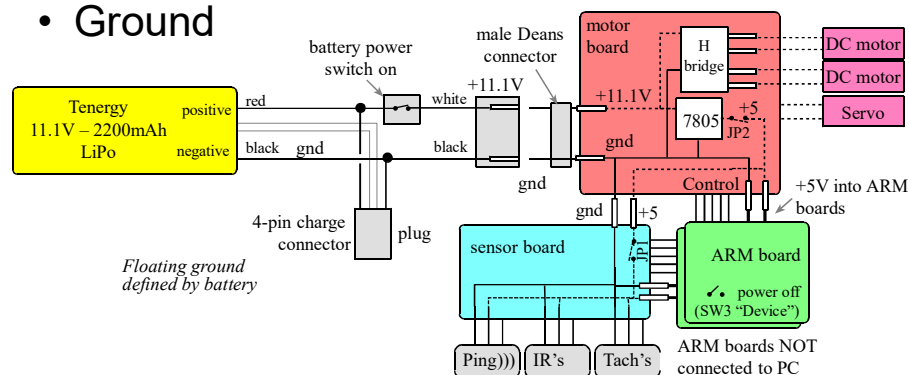
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23

Under Battery Power

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



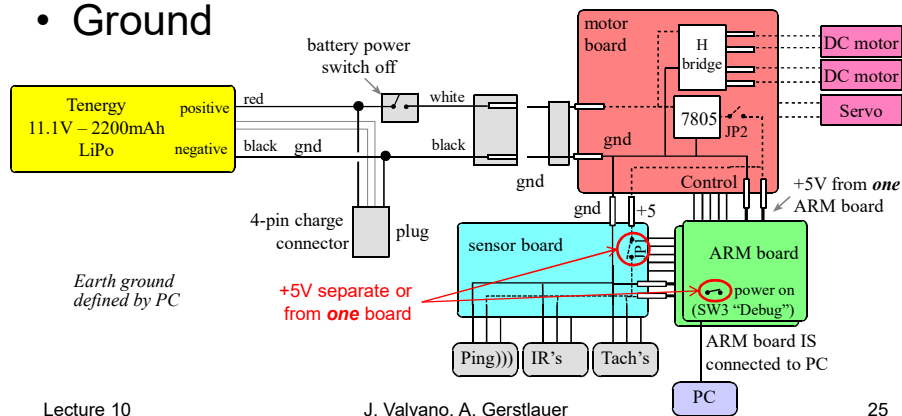
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24

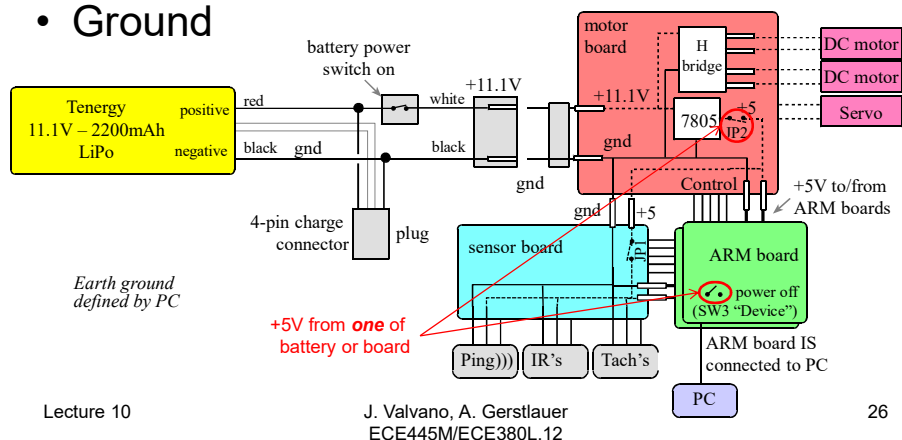
While Debugging with PC

- Battery disconnected (switch off)
- One or two separate +5V (jumper)
- Ground



Debugging with Motor

- Battery connected (switch on)
- One, two or three +5V (jumpers)
- Ground



Race Tracks

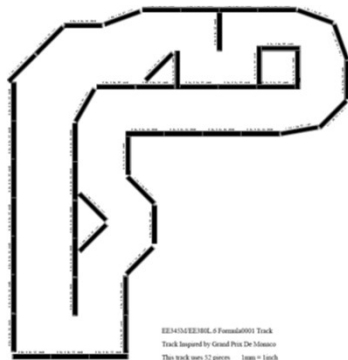


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27

Monaco



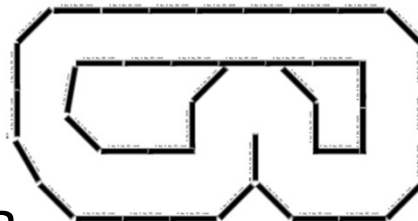
EE345M/EE380L.6 Formula0001 Track
Track Inspired by Grand Prix De Monaco
This track uses 32 pieces 1mm x 1 inch

Von Deutschland



EE345M/EE380L.6 Formula0001 Track
Track Inspired by FORMULA 1 GROSSER PREIS SANTANDER VON DEUTSCHLAND

Espana



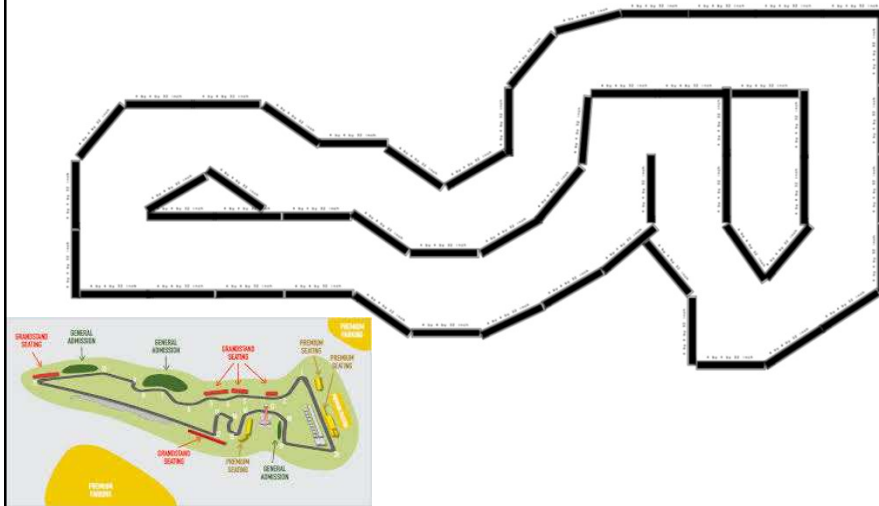
EE345M/EE380L.6 Formula0001 Track
Track Inspired by FORMULA 1 GRAN PREMIO DE ESPANA TELEFÓNICA

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Circuit of the Americas



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State Machine

- What is a state?
 - Something you believe to be true
- How do you get into a state?
 - Current state plus new input
- What do you do in a state?
 - Perform outputs, which parameter to control,
 - Do this for while
 - Collect input and change state

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30

State Machine

- Examples of states
 - The road is straight and clear
 - Gentle/moderate/sharp left/right turn
 - Going to hit the wall (brace for impact)
 - Hit the wall stupid
 - Slow moving robot ahead
 - Moving perpendicular to wall (lost)
 - Going the wrong way

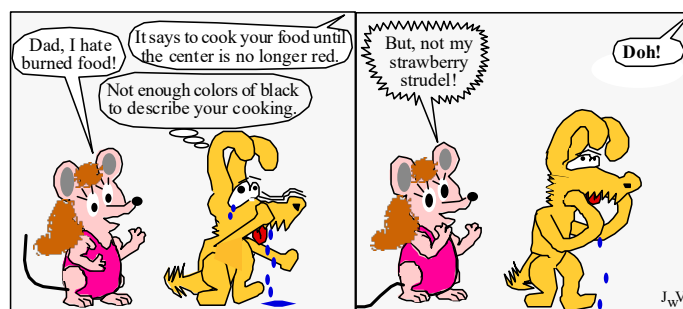
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Control Systems

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



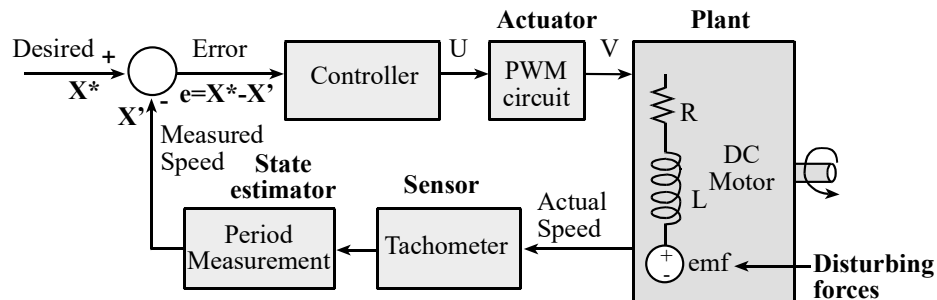
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32

Control System

- Estimated State Variables X'
- Desired State Variables X^* , setpoint



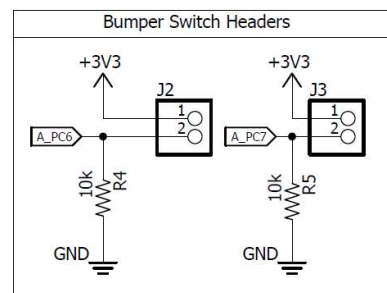
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What to Measure?

- Distance to wall
 - IR (median filter, calibration)
 - Ultrasound
 - Time-of-flight
- Angled distance to wall
- Four point “image”
- Bumper switches
 - Connector for two



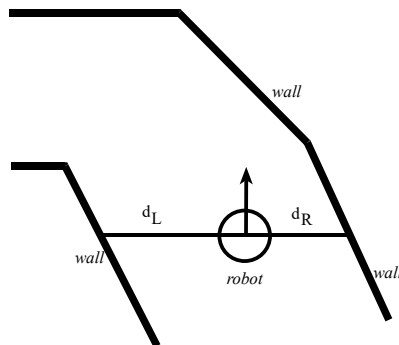
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34

What to Control?

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



Sensors

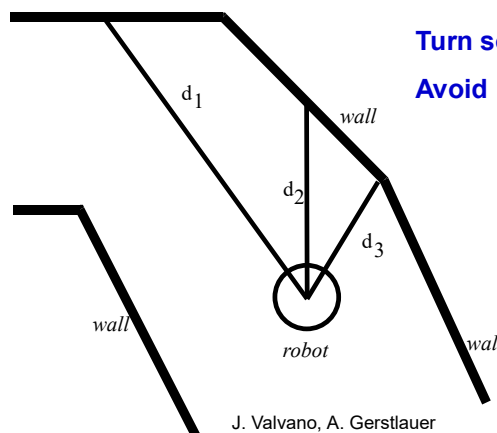
- Time constant $\rightarrow f_s$
- Filters
 - Analog, digital
- Signal/noise ratio
- Calibration
 - accuracy, drift

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What to Control?

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



Turn so most open in front
Avoid making U-turns

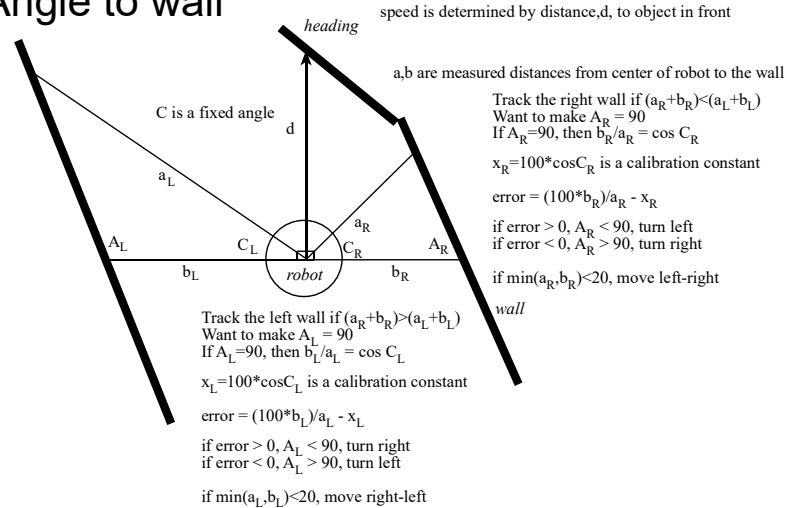
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36

What to Control?

- Angle to wall



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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

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38

How to turn?

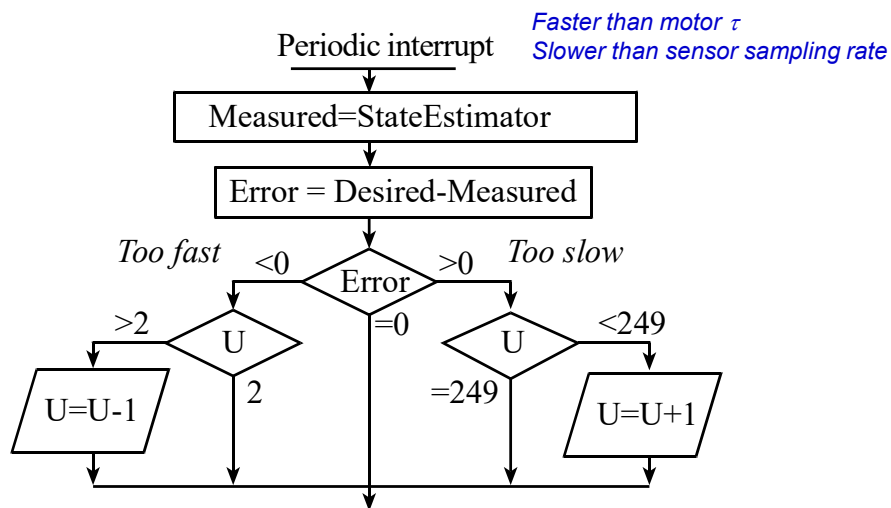
- Servo only
 - Servo_Duty(Steering);
- Servo plus differential drive, left turn
 - Servo_Duty(LeftSteering);
 - Left_Duty(LowPower,0);
 - Right_Duty(12500-HighPower,1);
- Servo plus differential drive, right turn
 - Servo_Duty(RightSteering);
 - Left_Duty(HighPower,0);
 - Right_Duty(12500-LowPower,1);

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Incremental Controller



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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;
}

```

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41

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

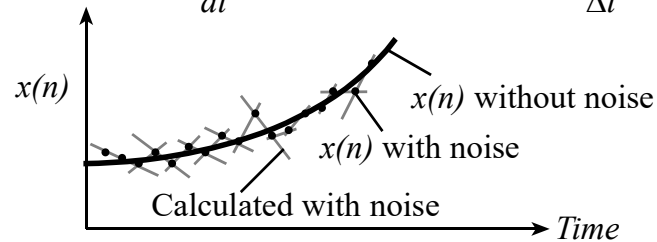
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42

Derivative Term

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



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

- Analog filter
- Digital filter

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

- Linear regression

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43

PI Controller

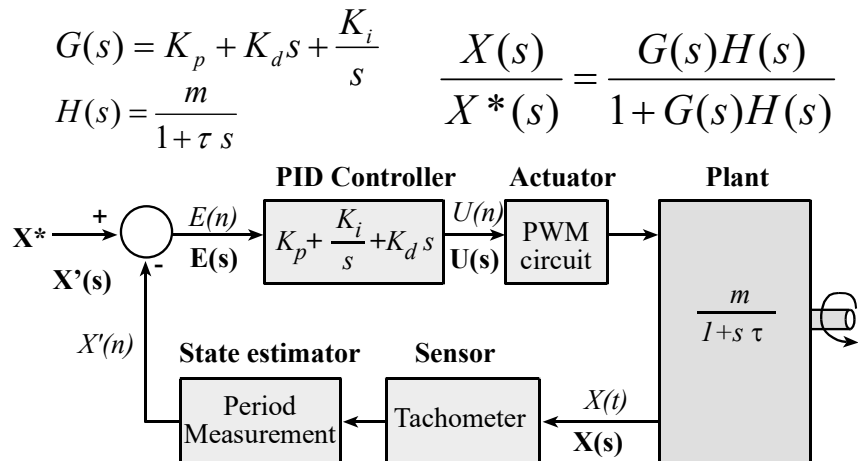
```
void Timer0A_Handler(void) {
    E = Xstar-X;
    P = (105*E)/20;           // Kp = 105/20
    I = I+(101*E)/640;        // KiΔt = 101/640
    if(I < -500) I=-500;      // anti-reset windup
    if(I > 4000) I=4000;
    U = P+I;                  // PI controller
    if(U < 100) U=100;        // Constrain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

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44

Laplace Domain



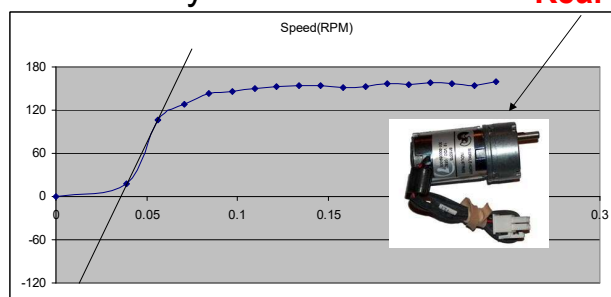
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45

Motor Parameters

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



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

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46

Controller Tuning

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

Highly nonlinear -> empirical approach

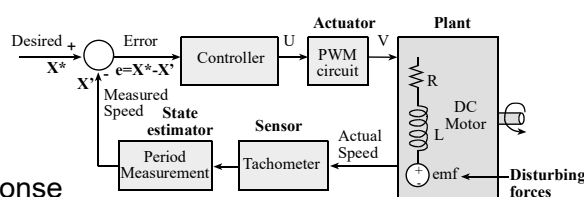
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47

Control Algorithms

- Incremental
 - + Simple, stable
 - Slow response
- PID or PI
 - + Theory, fast response
 - Needs empirical tuning, depends on load
- Many others... (see control theory)
 - Fuzzy logic: map human intuition into rules
 - Kalman filtering: state estimation from sensors
 - Optimal control: model predictive control (MPC)
 - ML: reinforcement learning
 - ...



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48

Fuzzy Logic

- 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

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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

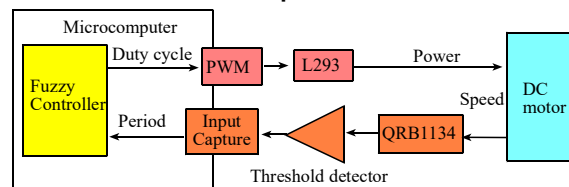
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50

Fuzzy 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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51

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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52

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 */
}

```

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53

Fuzzification

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

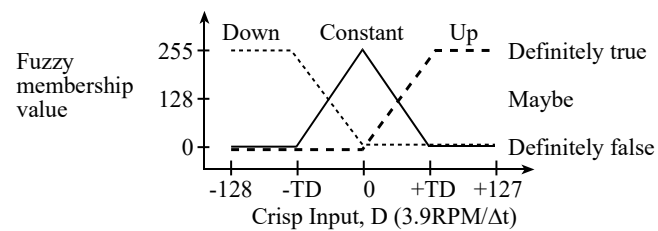
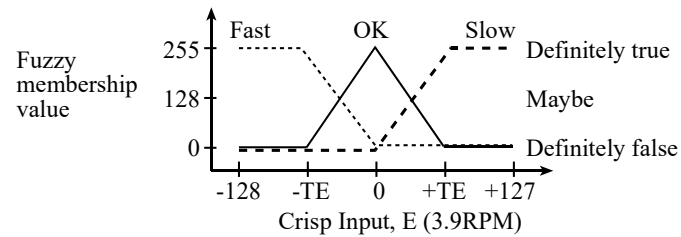
<i>Slow</i>	True if the motor is spinning too slow
<i>OK</i>	True if the motor is spinning at the proper speed
<i>Fast</i>	True if the motor is spinning too fast
<i>Up</i>	True if the motor speed is getting larger
<i>Constant</i>	True if the motor speed is remaining the same
<i>Down</i>	True if the motor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

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54

Fuzzification



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55

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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56

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*

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57

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);
}

```

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58

Fuzzy Rules

D		Down	Constant	Up
E	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)) ;
}

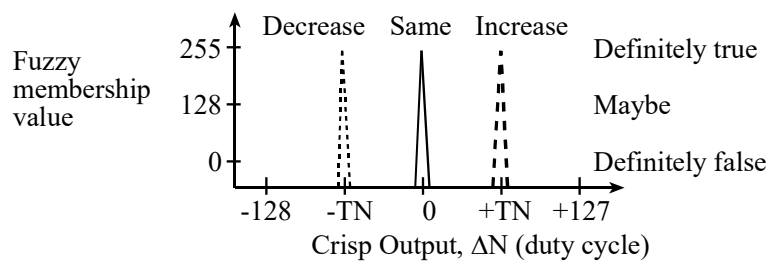
```

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59

Defuzzification



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

```

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

```

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60

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
}
```

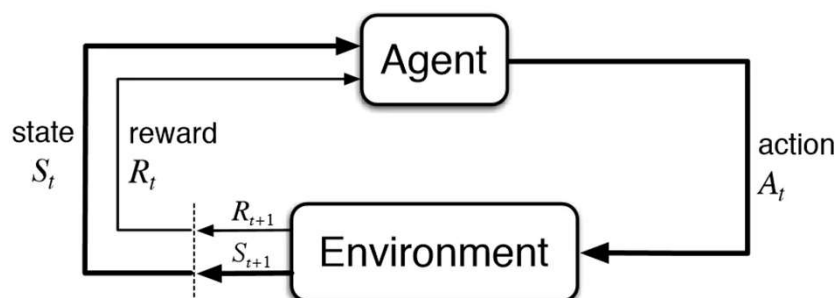
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61

Reinforcement Learning (RL)

- Agent learns a policy
 - Given current state S , what action A to take
 - Observe reward R and learn from past observations
 - Exploration vs. exploitation



Source: Sutton, Barto, "Reinforcement Learning: An Introduction," MIT Press, 2018.

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62

Q-Learning

- Q-Table
 - Pick action with highest Q value for given state
 - Update quality (Q) values after each step

Q-Table		Actions					
		South (0)	North (1)	East (2)	West (3)	Pickup (4)	Dropoff (5)
States	0	0	0	0	0	0	0
	1	.	.	.	.	.	.
	2	.	.	.	.	.	.
	3	.	.	.	.	.	.
	328	-2.30108105	-1.97092096	-2.30357004	-2.20591839	-10.3607344	-8.5583017
	.	.	.	.	.	.	.
	.	.	.	.	.	.	.
	499	9.96984239	4.02706992	12.96022777	29	3.32877873	3.38230603

$$Q^{new}(S_t, A_t) \leftarrow (1 - \underbrace{\alpha}_{\text{learning rate}}) \cdot \underbrace{Q(S_t, A_t)}_{\text{current value}} + \underbrace{\alpha}_{\text{learning rate}} \cdot \underbrace{\left(\underbrace{R_{t+1}}_{\text{reward}} + \underbrace{\gamma}_{\text{discount factor}} \cdot \underbrace{\max_a Q(S_{t+1}, a)}_{\text{estimate of optimal future value}} \right)}_{\text{new value (temporal difference target)}}$$

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Source: Wikipedia

63

Q-Learning Implementation

- Table-based approach fails for large spaces
 - Storage requirements
 - Very low update rates of each entry
- Quantize state-action space
 - Continuous -> discrete (e.g. close/far to wall)
- Approximate table as learned function
 - Neural network: deep Q-learning
 - Fuzzy rules

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64

Things that can go bad

- Hitting the wall
 - Think of three ways to tell if you hit the wall
 - Corrective measures
- Wrong-way Corrigan
 - 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

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65