

## EEE 480 Feedback Systems Outline

| Topic                    | Reading Material | Contents   |
|--------------------------|------------------|--|
| 1. Control Problems      | Ch.              | Quick introduction, general concepts and terminology of feedback systems, block diagrams.<br><br>Feedback versus feedforward, sensors and actuators, disturbances, uncertainty and robustness, stabilization, tracking, performance, sensitivity, optimality.  |
| 2. System Models         | Ch., handouts    | Modeling for control, ODE/state-space concepts, linearization, time-scaling.   |
| 3. Dynamic Response      | Ch.              | Quantifying properties of dynamic response. Laplace transforms and frequency domain description, block diagram algebra, transfer functions for feedback and interconnected systems.<br><br>Limit theorems, internal model principle<br>Partial fraction expansion<br>Effect of pole-zero locations on step response<br>Performance indicators (overshoot, damping, settling time, rise time, bandwidth, resonance frequency) |
| 4. Simple Controllers    | Ch.              | The PID controller. Lead and Lag compensators.   |
| 5. System Approximations | Handouts         | Understanding the notion of approximation in systems. Quantifying the dominant dynamics, modeling error. Model order reduction principles.<br><br>Handout examples.  |
| 6. System properties     | Ch.              | Stability, Routh   |
| 7. Design Tools          | Ch.<br>Ch.       | 1. Pole-placement (Root-locus, dominant target matching)<br>2. Loop-shaping (Bode/Nyquist)   |
| 8. Design Computations   | Ch.<br>Ch.       | Pole-placement (Lead-Lag Designs)<br>Loop-shaping (Lead-Lag Designs)   |

## NOTES

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| 1. | <p>Simple examples to motivate the study of feedback systems.</p> <p><b>General problem:</b><br/> Given a system <math>G: (u,d) \rightarrow y</math>, and a set of reference signals <math>y^*</math>, design a controller <math>C: (y,y^*) \rightarrow u</math>, such that <math>y \sim y^*</math>.<br/> Model-matching version: <math>G_c: r \rightarrow y</math>, <math>G_m: r \rightarrow y^*</math>. Find <math>C: (y,r) \rightarrow u</math> s.t. <math>C \sim G_m</math>.</p>  |
| 2. | <p><b>Modeling issues:</b><br/> We are primarily interested in the model <math>u \rightarrow y</math>.<br/> We need to know how the control input affects the output. We do not know the disturbances (certain "disturbances" can be measured leading to feedforward controllers) but we should know certain gross properties (spectrum, energy/power bounds). Similarly for modeling errors, we should know a bound on the so-called multiplicative uncertainty.</p> <p><b>Improving the design of control systems:</b><br/> More accurate models: Dynamic compensators, general design methods.<br/> Respect the uncertain: Design constraints, specifications/control objectives, feasibility</p>  |
| 3. | <p><b>Specifications:</b><br/> The difficult part is to translate linguistic specifications (well-behaved closed-loop, quick settling, reasonable overshoot, good disturbance attenuation) to quantitative ones (stability, damping ratio <math>&gt; 0.7</math>, Bandwidth <math>&gt; 1.3</math>, <math> S(jw)  &lt; -20</math> dB for <math>w</math> in <math>[0, 5]</math>, zero steady-state error to steps). Basic analytical tools help to define what is feasible and some of the necessary ingredients a compensator must possess.</p>   |
| 4. | <p>The general shape of compensators: An integral part for high gain at low frequencies, a derivative part to shape the crossover and a proportional part to adjust the level.</p>  |
| 5. | <p><b>Distance between systems:</b><br/> Peak magnitude of the frequency response of the difference <math>\max_w ( G_1(jw) - G_2(jw) )</math>. From this, a reduction of the model order can be achieved by eliminating small terms in the partial fraction expansion. Dominant modes = modes of the big terms. Near pole-zero cancellations, fast dynamics lead to terms with small residues. System approximation concepts are particularly useful in simplified designs.</p>   |
| 6. | <p>A nice analytical tool...</p>  |
| 7. | <p>The two basic analysis/design methods.<br/> <b>Root-Locus:</b> Determine how the roots of a polynomial move as we change the coefficients. (coefficients = affine functions of a single parameter).<br/> <b>Nyquist:</b> Complex analytic argument to determine the RHP roots of a polynomial.</p>   |
| 8. | <p>The controller computations. Dynamic compensators introduce poles and zeros to reshape the root-locus/Nyquist plots.<br/> -Root-locus design essentially works by shaping a dominant 2<sup>nd</sup> order approximation of the closed loop.<br/> -Nyquist/Bode design adjusts the loop transfer function around the crossover frequency.<br/> The choice depends on specifications and user preference. Usually, designs involve an interplay of the two, at least at the conceptual level.<br/> <b>Design Evaluation:</b><br/> Simulation, Experiment, Operation.<br/> Did we actually achieve the desired response? Do we need to iterate and what needs to be modified?</p> <p><b>What is hard?</b><br/> <i>In 480:</i> Root-locus, Nyquist plots, Design computations, Modeling (some)<br/> <i>In reality:</i> Modeling, Quantify modeling approximations, Estimate disturbance/uncertainty properties, Decide design specifications, Feasibility issues, Quantify performance, Optimality, Design computations (multiple objectives), Managing the global behavior (saturation handling, nonlinear effects), Maintenance Issues</p> |

| Week            | Instruction  | Lab  |
|-----------------|--|--|
| 1               | General Intro, Systems, Applications, Robustness-Performance trade-off. Modeling and Simulations (MATLAB).   | -  |
| 2               | Models for control, State-Space essentials, Linearization. Laplace review, PFE, Limit Value theorems. Block diagram algebra, Loop tf computations.   | #1. MATLAB/SIMULINK  |
| 3<br>HW1        | Step and frequency responses, 1-2-3 order, effects of pole/zero location, performance indicators. Control objectives, Basic controller shapes: PID-Lead/lag: Frequency resp of closed-loop, Sensitivity and Complementary sensitivity. 2DOF controllers, prefilters. | #1 cont.   |
| 4<br>HW2        | System approximations, dominant dynamics, unmodeled dynamics, Model-order reduction, uncertainty, robustness, Stability (Routh, 3 <sup>rd</sup> order example R/L crossings)   | #2 System Responses  |
| 5<br>EX1<br>HW3 | Root-Locus analysis: concept, computations. Real axis rule, asymptotes, breakaway points, angle of departure/arrival, RL patterns  | #2 cont.   |
| 6<br>HW4        | RL examples and design hints: design for a 2 <sup>nd</sup> order dominant CL system  | #3 Modeling and approximations, uncertainty estimates              |
| 7<br>EX2        | RL design  | #3 cont.   |
| 8<br>HW5        | Nyquist analysis: The basic theorem and examples   | #4 Simple R/L design (car)   |
| 9<br>HW6        | Nyquist-Bode (frequency domain) examples and Sensitivity properties, Loop shaping principles   | #4 cont.   |
| 10<br>EX3       | N/B Design   | #5 Simple N-B design (car)   |
| 11<br>HW7       | Lead-lag compensation (R/L-N/B)  | #6 Torque pendulum control (instability)                           |
| 12<br>HW8       | Case studies   |  |
| 13<br>EX4       | Case Studies, Nonlinear effects (saturation), Discretization   | #7 Temperature control (Saturation), Cart&Pendulum control (nasty) |
| 14              | Case Studies   | #7 cont.   |
| 15+<br>EX5      | Case Studies, Review   |  |