Instructor: Prof D.E. Davison, ddavison@uwaterloo.ca

Required background: Any first course in control (ECE 380, MTE 360, SYDE 352, ...), and any course in linear algebra.

Course objectives: The two high-level course objectives are:

1. Learn to think more like an advanced control engineer.
2. Become familiar with more powerful control analysis and design tools.

Lower-level objectives include:

(a) Recognize the benefits of feedforward and feedback control schemes.
(b) Explain fundamental performance limitations that arise in feedback control because of pole or zero locations in the plant.
(c) Analyze a control system to determine how robust it is with respect to uncertainty in the plant model.
(d) Understand complexities that arise in a multi-input multi-output (MIMO) setting, in particular the issue of cross-channel interaction.
(e) Perform basic calculations on a MIMO system (e.g., find the poles and zeros, interpret a MIMO Bode plot).
(f) Become familiar with the state-space framework as an alternative to the transfer function framework, and recognize the benefits of the state-space approach, especially for MIMO systems.
(g) Be proficient at manipulating MIMO block diagrams using both transfer function methods and state-space methods.
(h) Design controllers for MIMO systems using various transfer function techniques. Recognize situations where such techniques work well and do not necessarily work well.
(i) Master several standard, and very powerful, state-space control design techniques for MIMO systems.
(j) Be able to explain how state-space methods and transfer-function methods complement one another.

Main applications studied in class:

- simple mass-spring-damper systems
- control of a rocket (a tricky balancing problem!)
- control of a 747 airplane (a true multivariable system)
- a demo helicopter system (tethered for safety)
Textbook
An extensive set of lecture notes, exercises and solutions, plus all old exams will be available for purchase. Other references will be available for those who request them. (No textbook needs to be purchased.)

Scheduling for W2014 TBD

Marking scheme
<table>
<thead>
<tr>
<th>Project exercises</th>
<th>15%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Midterm exams</td>
<td>25%</td>
</tr>
<tr>
<td>Final exam</td>
<td>60%</td>
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</tbody>
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Project exercises
There is a set of six “project exercises” that you will work on throughout the term. The exercises are provided at the end of most sections of the notes. Each project exercise applies the methods of that section to a particular control system. The purpose of the project exercises is to increase your understanding of the techniques and ideas presented in the lectures by applying them to a quasi-realistic system. By working through the problems, you will also increase your familiarity with a popular numerical software package (Matlab) and learn to appreciate the limitations of such software. Project exercises can be done in groups, and the instructor will gladly work with students on any aspect of the exercises. The purpose of the exercises is to learn the material better.

Project grading
Each Project Exercise will be graded out of three, roughly as follows:

- 3/3 = essentially correct and complete, possibly with a few trivial errors
- 2/3 = minor errors or minor omissions or presentation problems
- 1/3 = major errors or major omissions or terrible presentation
- 0/3 = essentially wrong or totally incomplete or incomprehensible

Project topic
The project this term deals with various balancing systems, such as that shown below:

\[
\begin{bmatrix}
F \\
\tau_1 \\
\tau_2 \\
x_u \\
y_u \\
w
\end{bmatrix} =
\begin{bmatrix}
0 & 1 & 0 & 0 & 0 \\
0 & 0 & -3.2667 & 0 & 0 \\
0 & 0 & 0 & 1 & 0 \\
0 & 0 & 19.600 & 0 & 0 \\
1 & 0 & 0 & 0 & 0 \\
0 & 0 & 1 & 0 & 0
\end{bmatrix}
\begin{bmatrix}
x \\
x \\
x \\
x \\
\end{bmatrix} +
\begin{bmatrix}
0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 1 & 0 \\
0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 1 & 0 \\
0 & 0 & 0 & 0 & 0
\end{bmatrix}
\begin{bmatrix}
u \\
u \\
u \\
u \\
u
\end{bmatrix}
\]
1. Introduction [2 lectures]
   - What’s control engineering all about?
   - What’s new in this course?
   - Applications of control
   - A review of the control engineering design cycle
   - Some useful Matlab commands

2. Design for SISO Systems—Part 1: Classical techniques [5 lectures]
   - Signals and Systems Basics
   - Stability of Interconnected Systems and the Routh-Hurwitz Stability Test
   - Steady-state Calculations
   - Transient Response Calculations
   - Root Locus Methods
   - Nyquist Plots, Phase and Gain Margins, Lead and Lag Compensation
   - Introduction to the Small Gain Theorem
   - Introduction to Loopshaping

   - Limitations on Stabilization (Youla parameterization)
   - The Sensitivity and Complementary Sensitivity Functions: Performance Limitations due to Control Topology
   - Performance Limitations due to ORHP Poles (time domain and frequency domain)
   - Performance Limitations due to ORHP Zeros (time domain and frequency domain)
   - Performance Limitations if there are both ORHP Zeros and ORHP Poles

4. Design for MIMO Systems—Part 1: Use of transfer function techniques [7 lectures]
   - Basic MIMO concepts
   - Breaking a MIMO problem up into a series of SISO problems
   - Extending SISO Transfer Function Methods: MIMO Nyquist, etc.
   - Extending SISO Transfer Function Methods: MIMO Loopshaping
   - MIMO performance limitations

5. Design for MIMO Systems—Part 2: Use of state-space techniques [8 lectures]
   - Basic state-space facts and manipulations
   - Controllability, observability, stabilizability, and detectability
   - State-feedback control (pole placement)
   - Observers, state-feedback using observers, and the separation principle
   - Addition of integral control

   - Motivation
   - LQR Optimal Control Problem
   - LQR Solution
   - Optimal Observers
   - Important Example