An Introduction to Digital Linear Systems: Signals & Controls

Welcome!

ELEC 3004: Systems: Signals & Controls
Dr. Surya Singh

Lecture 1 [V2]

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http://robotics.itee.uq.edu.au/~elec3004/

February 27, 2019
Ref: Rippel, Nair, Lew, et al. Learned Video Compression, arxiv: 1811.06981, 16 Nov 2018
URL: http://www.rucoo.com/video-compression

Ref: Google RAISR, Wikipedia Aliasing
Mathematica:
waveani = Animate[Plot[Sin[a x] + Sin[b x], {x, 0, 10}, PlotRange -> 2], {a, 1, 5}, {b, 1, 5}, AnimationRunning -> True]
• PS. While we cover the theory why this is hard 😊, we don’t cover how to actually do this in this class (as it requires an extensive face database) 😞.

• However, for a great review please see:
  DOI: [http://dx.doi.org/10.1109/tpami.2002.1033210]
Example 7: Computational Imaging

- Intensity $\ell(.)$
- Position (3)
- Direction (2)
- Time (1)
- Wavelength (1)
- Polarization (1)
Another Example: Computational Imaging

- Flutter Shutter

What’s a Signal?

≡ A set of data or information

- Can be a function of in space and/or time

- Various types: electrical, economics, dating, etc.

- Data “information” is a process of understanding its structure/forms:

$$\sin(\omega t)$$
What is a System?

≡ A **process** (function) by which information (signals) are modified so as to extract additional information from them

• Systems modify the signal(s) to yield a new result (also a signal)

• Can be of various forms: electrical, mechanical, etc.

\[ F(x) \]

Systems Can Be Simpler Than You Think

• B747
  – level flight,
  – 40000 ft, 774 ft/sec …

\[
\begin{bmatrix}
\dot{u} \\
\dot{v} \\
\dot{q} \\
\dot{\theta}
\end{bmatrix} =
\begin{bmatrix}
-0.03 & 0.039 & 0 & -322 \\
-0.05 & -0.219 & 7.74 & 0 \\
0.20 & -0.101 & -0.429 & 0 \\
0 & 0 & 1 & 0
\end{bmatrix}
\begin{bmatrix}
u - u_{ref} \\
v - v_{ref} \\
q \\
\theta
\end{bmatrix}
+ 
\begin{bmatrix}
0.01 & 1 & 0 & 0 \\
-0.18 & -0.04 & 0 & 0 \\
-1.16 & 0.598 & 0 & 0
\end{bmatrix}
\begin{bmatrix}
\delta_e \\
\delta_t
\end{bmatrix}
\]

– u, w: horizontal/vertical velocity
– q, \( \theta \): orientation & pitch rate
– \( \delta e, \delta t \): elevator and thrust commands

Source: Boyd, Stanford EE263 Lecture 14 (Slide 14-4)
A signal can be seen as that which goes in and out of a system.

Signal Processing / “Filters”: can be seen as a open-loop system.

Feedback Control: can be viewed as the case where the output signal shapes the input signal.
Introducing ELEC3004/7312

Website: http://robotics.itee.uq.edu.au/~elec3004/

http://elec3004.com

http://openplatypus.org
Schedules and Locations:

• Lectures:
  – **Wednesdays** from **10:05 am – 12:00 noon**
  – Social Science Building (24) – Room S304
  – [Here! 😊]

  &

  – **Fridays** from **4:05 -- 5:30 pm**
  – Parnell (Physics) Building (07) – Room 234

• It starts at 10:05a (or 4:05p on Fridays) ➔ 🕒 Relax!

Schedules and Locations: **Tutorials**

• **Tutorials:** **EVEN Weeks (Starting on Week 2)**
  SIX parallel sessions -- **Please come to your assigned one.**
  • Alternate attendance is at tutor discretion and must be arranged in advance

• Sessions are:
  – **Wednesday 4:00p--6:00** in Hawken - Room S202
  – **Thursday 9:00a--11:00** in Hawken - Room S202
  – **Thursday 12:00n--2:00** in Hawken - Room S202
  – **Thursday 2:00p--4:00** in Hawken - Room S202
  – **Thursday 4:00p--6:00** in Hawken - Room S202
  – **Friday 2:00p--4:00** in Hawken - Room S202

• ~ 1.5 hours
Schedules and Locations: Labs

• Prac / Lab Sessions: **ODD Weeks (Starting Week 3)**
  - Six parallel sessions -- **Please come to your assigned one.**
  - Alternate attendance is at tutor discretion and must be arranged in advance

• Sessions are:
  - **Wednesday 4:00p--6:00** in Hawken - Room S202
  - **Thursday 9:00a--11:00** in Hawken - Room S202
  - **Thursday 12:00n--2:00** in Hawken - Room S202
  - **Thursday 2:00p--4:00** in Hawken - Room S202
  - **Thursday 4:00p--6:00** in Hawken - Room S202
  - **Friday 2:00p--4:00** in Hawken - Room S202

• ~ 2 hours

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Lecture Schedule:

<table>
<thead>
<tr>
<th>Week</th>
<th>Date</th>
<th>Lecture Title</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>27-Feb</td>
<td><strong>Introduction</strong></td>
</tr>
<tr>
<td></td>
<td></td>
<td>1-Mar Introduction to Feedback Control</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2-Mar Servo regulation/PID</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3-Mar State Space Control</td>
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<tr>
<td></td>
<td></td>
<td>4-Mar Digital Filters (IIR) &amp; Filter Analysis</td>
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<tr>
<td></td>
<td></td>
<td>5-Mar Digital Filters (FIR)</td>
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<tr>
<td></td>
<td></td>
<td>6-Mar Digital Windows</td>
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<tr>
<td></td>
<td></td>
<td>7-Mar Active Filters &amp; Estimation &amp; Holiday</td>
</tr>
<tr>
<td></td>
<td>13-Apr</td>
<td>Holiday</td>
</tr>
<tr>
<td></td>
<td>19-May</td>
<td>Summary and Course Review</td>
</tr>
</tbody>
</table>
Reference Texts:

• Yes!
  You may use the Internet!!
  – Khan Academy
  – Wikipedia
  – YouTube
  – & Google Scholar Too!

• This field is vast & there are countless references present

The Point of the Course

• Introduction to terminology/semantics
• An appreciation of how to frame problems in a linear systems engineering context
• Modeling and learning assumptions/when to trust the model
• Ability to identify critical details from the problem

➤ It’s a shortcut …
Once you see that a system is “linear” you can then apply the raft of
“linear systems” tools (time & frequency analysis) to them without having to do all the analysis from scratch
Not the Point of the Course

- Get good grades
- Just do homework
- Memorize pointless facts
- Rote “learning” of material with no comprehension
- Ask yourself, is the wonder still there?

Lots of Stuff To Cover…

- Systems
- Signal Abstractions
- Signals as Vectors / Systems as Maps
- Linear Systems and Their Properties
- LTI Systems
- Autonomous Linear Dynamical Systems
- Convolution
- FIR & IIR Systems
- Frequency domain
- Fourier Transform (CT)
- Fourier Transform (DT)
- Even and Odd Signals
- Likelihood
- Causality
- Impulse Response
- Root Locus
- Bode Functions
- Left-hand Plane
- Frequency Response
- Discrete Time
- Continuous Time
- Laplace Transformation
- Feedback and Control
- Additional Applications
- Linear Functions
- Linear Algebra Review
- Least Squares
- Least Squares Problems
- Least Squares Applications
- Matrix Decomposition and Linear Algebra
- Regularized Least Squares
- Least-squares
- Least-squares applications
- Orthonormal sets of vectors
- Eigenvectors and diagonalization
- Linear dynamical systems with inputs and outputs
- Symmetric matrices, quadratic forms, matrix norm, and SVD
- Controllability and state transfer
- Observability and state estimation
- And that, of course, Linear Systems are Cool! 😊
Assessment

- **Problem Set 1:**
  An Introduction to Signals and Systems (20%)
  Due: March 29, 2019 at 23:59 AEST [end of week 4]

- **Problem Set 2:**
  Sampling and Filters (Digital & Analog) (20%)
  Due: May 3, 2019 at 23:59 AEST [end of week 9]

- **Problem Set 3:**
  Digital Feedback Control (20%)
  Due: May 24, 2019 at 23:59 AEST [end of week 12]

**Platypus: Peer-review for Deliberate Practice/Learning**

- **Peer-Review**
  - A **key** part of Engineering is being able to critically evaluate peer work (and give **good** feedback on it)
  - We **will** help teach you good habits of peer feedback

- **Question** (not Assignment)
  based random shuffling
**Platypus: How does it work?**

I. Collect Assignments (one per student):

![Diagram of Platypus: How does it work?]

II. Randomly shuffle questions between assignments to create $kM$ "Papers" (where $k$ is the peer review factor, or the number of papers a student needs to review, eg 3)

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**In Summary: Some Philosophy**

- Let’s start with Why …

- To learn something is to teach it
  - The function of a teaching is not so much to cover the topics, but more to discover them

- It is actually **more** work for us!
  - We have to teach you how to reflect
    & then assess this as well as how to do the assignment

- It helps you understand it by giving you a different perspective

- We’re a community
  - You (alone) can’t do everything … that’s why we work together
  - The notion of “free speech” $\Rightarrow$ Trust emerges $\Rightarrow$ efficiency ($\eta$)
Last Year’s Grade Statistics

• ~62% received >4 and ~30% received D or HD
• Worry about **learning**, not about marks

GRADE INFLATION

AVERAGE  BELOW AVERAGE  COMPLAIN UNTIL YOU GET A BETTER GRADE  THE DEAN GETS INVOLVED  FILE LAWSUIT  IN COMPLETE DENIAL

[Website: www.phdcomics.com]
How to Get a Job at Google

FEB 22, 2014

Mountain View, Calif. — LAST June, in an interview with Adam Bryant of The Times, Laszlo Bock, the senior vice president of people operations for Google — i.e., the guy in charge of hiring for one of the world’s most successful companies — noted that Google had determined that “G.P.A.’s are worthless as a criteria for hiring, and test scores are worthless. We found that they don’t predict anything.” He also noted that the “proportion of people without any college education...”

Information: Size and Rate

<table>
<thead>
<tr>
<th>Information Type</th>
<th>Size/Bits/Rate</th>
<th>Size/Bits/Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>A short novel</td>
<td>1 megabyte</td>
<td>1,000,000</td>
</tr>
<tr>
<td>All undergraduate textbooks</td>
<td>100 MB</td>
<td>100,000,000</td>
</tr>
<tr>
<td>An iPod</td>
<td>100 GB</td>
<td>80,000,000,000</td>
</tr>
<tr>
<td>A library floor of academic journals</td>
<td>100 GB</td>
<td>100,000,000,000</td>
</tr>
<tr>
<td>Print collections of Library of Congress</td>
<td>10 TB</td>
<td>10,000,000,000,000</td>
</tr>
<tr>
<td>Copying notes by hand</td>
<td>32 bits/second</td>
<td>32 bps</td>
</tr>
<tr>
<td>Speaking</td>
<td>230 bits/sec.</td>
<td>230 bps</td>
</tr>
<tr>
<td>Reading text</td>
<td>360 bits/sec.</td>
<td>360 bps</td>
</tr>
<tr>
<td>Home internet connection</td>
<td>1-10 Mb/sec.</td>
<td>5,000,000 bps</td>
</tr>
<tr>
<td>Single optical fiber</td>
<td>40 Gb/sec.</td>
<td>40,000,000,000 bps</td>
</tr>
</tbody>
</table>

A short novel ≈ 1 Mbyte

70 hours to copy
6 hours to read
Less than 10 seconds to download

Taken from: http://burkmodeldesign.com/search/How_Many_Bytes.htm
Changes from 2017

1. Three Assignments (Peer-reviewed, Marks from Tutor)

2. Labs remain optional
   1. Concepts still overlap with class
   2. May be assessed on Assignments/Final Exam

3. No State-Space Control “crammed” in the end

4. I am still inspired by, but little less of,
   Boyd’s EE263: Introduction to Linear Dynamical Systems

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E-mail

- **elec3004@itee.uq.edu.au**

- Casper!
  - [Link](https://casper.ceit.uq.edu.au/courses/elec3004/)

- [That’s it!]
- {Not the instructors/tutors personally}
Communications: Some Expectations

• Think carefully before using email

• Please keep communication concise and polite

• Let me know if there are problems
  – During tutorials, before and after lectures
  – Student reps (Teaching and Learning Committee)
  – Consultation period: 4-6pm Thursday

Communications: Examples

• Email 1:
  To [ELEC3004],
  I am currently signed up for the Tuesday afternoon tutorial, T1, but this clashes with another subject in which I have no movement. Is it possible for me to be changed into the Wednesday morning tutorial, T2? Thank You for your time.
  Name signed,
  student number

• Email 2:
  S’up!! 😊
  all T classes be the full, can’t sign on 😗
About What I Do

(a) Lesion targeting (b) DermBot (c) Visual Deformable Object Analysis (d) Neurosurgical Robotics
Q1: Complex Solutions to Real Problems

Can an ODE with only real constant coefficients have a complex solution?

- Yes, because the coefficients do not give the solution, but rather setup an equation that instead gives a solution

- For example: \( y'' + y = 0 \)

- Has solutions: \( e^{ix} \) and \( e^{-ix} \)
Q2: Transfer Functions and the s-Domain [1]

Final Value Theorem
\[ \lim_{t \to \infty} f(t) = \lim_{s \to 0} sF(s) \]

• For systems that are valid (i.e., stable):
  – Roots of the denominator of \( H(s) \) must have negative real parts.
  – \( H(s) \) must not have more than one pole at the origin.

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Q2: Transfer Functions and the s-Domain [2]

\[ G_a(s) = \frac{3004}{s+4} \]
\[ G_b(s) = \frac{3004}{s-4} \]
Q2: Transfer Functions and the $s$-Domain

- $G_c(s) = \frac{3004}{s^2+4}$
- $G_d(s) = \frac{3004}{s^4+4}$

Not a “dynamic system”
Q2: Transfer Functions and the $s$-Domain [2]

- $G_a(s) = \frac{3004}{s+4}$
- $G_b(s) = \frac{3004}{s-4}$

Matlab Source for Graphs

```matlab
% ELEC 3004 Quiz 0 -- Q2
Ga
a=[3004]; b=[1 4]; Ga=tf(a, b); figure(10); impulse(Ga); title('Impulse Response of G_a');
Gb
a=[3004]; b=[1 -4]; Gb=tf(a, b); figure(20); impulse(Gb); title('Impulse Response of G_b');
Gc
a=[3004]; b=[1 0 4]; Gc=tf(a, b); figure(30); impulse(Gc); title('Impulse Response of G_c');
Gd
a=[3004]; b=[1 0 0 4]; Gd=tf(a, b); figure(40); impulse(Gd); title('Impulse Response of G_d');
Ge
a=[3004]; b=[1 4 0]; Ge=tf(a, b); figure(50); impulse(Ge); title('Impulse Response of G_e');
Gf
a=[3004]; b=[4]; Gf=tf(a, b); figure(60); impulse(Gf); title('Impulse Response of G_f');
Q3: Free Determination

- False:
  \[ \det(A + B) \neq \det(A) + \det(B) \]

- True:
  \[ \det(AB) = \det(A) \cdot \det(B) \]

Q4: Free Determination : All TRUE

- True:
  \( A = LU \): is a factorization that is basically an elimination

- True:
  If \( A \) is invertible, then the only solution to \( Ax = 0 \) is \( x = 0 \).

- True:
  Linear Equations \( (Ax = b) \) come from steady-state problems. Eigenvalues \( (Ax = \lambda x) \) have importance in dynamic problems.
Q5: Convolution!: All TRUE

\[
\dot{\theta} = \frac{\Delta \theta}{\Delta t} = \left[\frac{(2n+1)\pi}{25}\right] \Rightarrow 12.5 \text{ rev/second}
\]

B. Speeds (m/s):
\[
v = \omega \times r = 25\pi \frac{\text{rad}}{s} \cdot (0.32 \text{ m}) = 25.1 \frac{\text{m}}{s} = 90.5 \text{ km/h}
\]

C. Speed_{\text{car}} = \text{Speed}_{\text{wheel}}:
- Straight line (no turning)
- Full traction
- No suspension effects …
- What is the frame of reference? Should be picked with care!

Q6: A Signal Re-\text{volution}!

Frame 1  Frame 2  Frame 3  Frame 4

A. It could be rotating either way (CW or CCW). The angular velocity is \[ \dot{\theta} = \frac{\Delta \theta}{\Delta t} = \left[\frac{(2n+1)\pi}{25}\right] \Rightarrow 12.5 \text{ rev/second} \]
Next Time...

- We’ll talk about System Models

- Review:
  - Phasers, complex numbers, polar to rectangular, and general functional forms.
  - Chapter 1 of Lathi
    (particularly the first sections on signals & classification thereof)

- Register on Platypus

- Try the practise assignment (will be posted soon)