ESE 531: Digital Signal Processing

Lec 1: January 12, 2017
Introduction and Overview
Where I come from

- Analog VLSI Circuit Design
- Convex Optimization
  - System Hierarchical Optimization
- Biomedical Electronics
- Biometric Data Acquisition
  - Compressive Sampling
- ADC Design
  - SAR, Pipeline, Delta-Sigma
- Low Energy Circuits
  - Adiabatic Charging
Minimally Invasive Implant to Combat Healthcare Noncompliance

- Model for implants: reconfigurable RFID tags that continuously record specific biometric
  - During the read operation, energy storage element is recharged
- Size of package small enough to allow injection
- Actigraphy expected to be clinically useful
  - Platform allows for any sensor that gathers information on a slow time scale
MicroImplant: An Electronic Platform for Minimally Invasive Sensory Monitors
Sample at lower than the Nyquist rate and still accurately recover the signal, and in some cases exactly recover.
Example: Sum of Sinusoids

Sense signal randomly $M$ times
- $M > C \cdot \mu \cdot \log N$

Recover with linear program
Biometric Example: Parkinson’s Tremors

- 6 Subjects of real tremor data
  - collected using low intensity velocity-transducing laser recording aimed at reflective tape attached to the subjects’ finger recording the finger velocity
  - All show Parkinson’s tremor in the 4-6 Hz range.
  - Subject 8 shows activity at two higher frequencies
  - Subject 4 appears to have two tremors very close to each other in frequency
Biometric Example: Parkinson’s Tremors

- C=10.5, T=30
  - 20% Nyquist required samples
Lecture Outline

- Course Topics Overview
- Learning Objectives
- Course Structure
- Course Policies
- Course Content
- Industry Trends
- Design Example
Course Topics Overview

- Discrete-Time (DT) Signals
- Time-Domain Analysis of DT Systems
- Discrete Fourier Transform (DFT)
- Fast Fourier Transform (FFT)
- Discrete-Time Fourier Transform (DTFT)
- z-Transform
- Sampling of Continuous Time Signals
- Data Converters and Modulation
- Upsampling/Downsampling
- Discrete-Time Filter Design
Learning Objectives

- Learn the fundamentals of digital signal processing
- Provide an understanding of discrete-time signals and systems and digital filters
- Enable you to apply DSP concepts to a wide range of fields
- Gain the ability to read the technical literature on DSP
- Apply the techniques learned in a final project encompassing many different application types
Learning Objectives

- In other words…

- **Math, Math, Math***

  *With MATLAB application for intuition*
Course Structure

- **TR Lecture, 4:30-6:00pm in Towne 303**
  - Start 5 minutes after, end 5 minutes early (~75-80min)
- **Website (http://www.seas.upenn.edu/~ese531/)**
  - Course calendar is used for all handouts (lectures slides, assignments, and readings)
  - Canvas used for assignment submission and grades
  - Piazza used for announcements and discussions
Course Structure

- **Course Staff (complete info on course website)**
- **Instructor: Tania Khanna**
  - Office hours – Wednesday 2-4:30 pm or by appointment
  - Email: taniak@seas.upenn.edu
    - Best way to reach me
- **TA: Shlesh Tiwari**
  - Office hours – TBD
Course Structure

- Lectures
  - Statistically speaking, you will do better if you come to lecture
  - Better if interactive, everyone engaged
    - Asking and answering questions
    - Actively thinking about material

- Textbook
  - Class will follow text structure… mostly
Course Structure - Assignments/Exams

- **Homework** – 1-2 week(s) long (8 total) [25%]
  - Due Thursdays at start of class (1:30pm)
  - Combination of book problems and matlab problems
    - MATLAB problems not optional

- **Project** – two+ weeks long (2 total) [30%]
  - Combination of different DSP applications

- **Midterm exam** [20%]

- **Final exam** [25%]
Course Policies

See web page for full details

- Turn homework in Canvas before lecture starts
  - Anything handwritten/drawn must be clearly legible
  - Submit CAD generated figures, graphs, results when specified
  - NO LATE HOMEWORKS!

- Individual work (except project)
  - CAD drawings, simulations, analysis, writeups
  - May discuss strategies, but acknowledge help
Course Content

- Introduction
- Discrete Time Signals & Systems
- Discrete Time Fourier Transform
- Z-Transform
- Inverse Z-Transform
- Sampling of Continuous Time Signals
- Frequency Domain of Discrete Time Series
- Downsampling/Upsampling
- Data Converters, Sigma Delta Modulation
- Frequency Response of LTI Systems
- Signal Flow Representation
- Basic Structures for IIR and FIR Systems
- Design of IIR and FIR Filters
- Butterworth, Chebyshev, and Elliptic Filters
- Filter Banks
- Adaptive Filters
- Computation of the Discrete Fourier Transform
- Fast Fourier Transform
# ESE531 Spring 2017 Working Schedule

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This working calendar is on the web [here](http://www.eese.upenn.edu/~ese531/spring2017/working.html). Please, recheck the page on the web as details may be adjusted as the term progresses. Lectures notes, reading, and handouts will be listed as we reach them.
What is DSP
DSP is Everywhere

- Sound applications
  - Compression, enhancement, special effects, synthesis, recognition, echo cancellation,…
  - Cell Phones, MP3 Players, Movies, Dictation, Text-to-speech,…

- Communication
  - Modulation, coding, detection, equalization, echo cancellation,…
  - Cell Phones, dial-up modem, DSL modem, Satellite Receiver,…

- Automotive
  - ABS, GPS, Active Noise Cancellation, Cruise Control, Parking,…

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DSP is Everywhere (con’t)

- **Medical**
  - Magnetic Resonance, Tomography, Electrocardiogram, Biometric Monitoring…

- **Military**
  - Radar, Sonar, Space photographs, remote sensing,…

- **Image and Video Applications**
  - DVD, JPEG, Movie special effects, video conferencing,…

- **Mechanical**
  - Motor control, process control, oil and mineral prospecting,…
Humans are the most advanced signal processors
- speech and pattern recognition, speech synthesis,…

We encounter many types of signals in various applications
- Electrical signals: voltage, current, magnetic and electric fields,…
- Mechanical signals: velocity, force, displacement,…
- Acoustic signals: sound, vibration,…
- Other signals: pressure, temperature,…

Most real-world signals are analog
- They are continuous in time and amplitude
- Convert to voltage or currents using sensors and transducers
Analog circuits process these signals using
- Resistors, Capacitors, Inductors, Amplifiers,…

Analog signal processing examples
- Audio processing in FM radios
- Video processing in traditional TV sets
Limitations of Analog Signal Processing

- Accuracy limitations due to
  - Component tolerances
  - Undesired nonlinearities
- Limited repeatability due to
  - Tolerances
  - Changes in environmental conditions
    - Temperature
    - Vibration
- Sensitivity to electrical noise
- Limited dynamic range for voltage and currents
- Inflexibility to changes
- Difficulty of implementing certain operations
  - Nonlinear operations
  - Time-varying operations
- Difficulty of storing information

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Digital Signal Processing

- Represent signals by a sequence of numbers
  - Sampling and quantization (or analog-to-digital conversion)
- Perform processing on these numbers with a digital processor
  - Digital signal processing
- Reconstruct analog signal from processed numbers
  - Reconstruction or digital-to-analog conversion

- Analog input $\rightarrow$ analog output
  - Eg. Digital recording music
- Analog input $\rightarrow$ digital output
  - Eg. Touch tone phone dialing, speech to text
- Digital input $\rightarrow$ analog output
  - Eg. Text to speech
- Digital input $\rightarrow$ digital output
  - Eg. Compression of a file on computer

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Pros and Cons of Digital Signal Processing

- **Pros**
  - Accuracy can be controlled by choosing word length
  - Repeatable
  - Sensitivity to electrical noise is minimal
  - Dynamic range can be controlled using floating point numbers
  - Flexibility can be achieved with software implementations
  - Non-linear and time-varying operations are easier to implement
  - Digital storage is cheap
  - Digital information can be encrypted for security
  - Price/performance and reduced time-to-market

- **Cons**
  - Sampling causes loss of information
  - A/D and D/A requires mixed-signal hardware
  - Limited speed of processors
  - Quantization and round-off errors
DSP Examples
Example I: Audio Compression

- Compress audio by 10x without perceptual loss of quality.
- Sophisticated processing based on models of human perception
- 3MB files instead of 30MB
  - Entire industry changed in less than 10 years!
Historical Forms of Compression

- **Morse code**: dots (1 unit) dashes (3 units)
  - Code Length inversely proportional to frequency of character
    - E (12.7%) = . (1 unit) Q (0.1%) = --.- (10 units)

- **“92 Code”**
  - Used by Western-Union in 1859 to reduce BW on telegraph lines by numerical codes for frequently used phrases
    - 1 = wait a minute
    - 73 = Best Regards
    - 88 = Loves and Kisses
Example II: Digital Imaging Camera
Example II: Digital Imaging Camera
Example II: Digital Imaging Camera

- Compression of 40x without perceptual loss of quality.

- Example of slight overcompression: difference enables x60 compression!
Now implemented in smart phones (HDR)
Image Processing - Saves Children

Canadian 'swirl face' pedophile jailed in Thailand

August 15, 2008

Images released by Interpol in 2007 show the 'unswirling' of the internet pictures that led to the capture of Christopher Paul Neil.
Example III: MRI

k-space (raw data) \hspace{4cm} \text{Image}

\text{Discrete Fourier transform}
fMRI example

- Sensitivity to blood oxygenation
  - response to brain activity Convert from one signal to another
Compressive Sampling

- Compression meets sampling
Example IV: Software Defined Radio

- Traditional radio:
  - Hardware receiver/mixers/demodulators/filtering
  - Outputs analog signals or digital bits

- Software Defined Radio:
  - Uses RF font end for baseband signal
  - High speed ADC digitizes samples
  - All processing chain done in software
Software Defined Radio

Software Defined Radio

- Flexible RF Hardware
- ADC
- DAC
- IF
- Channelization and Sample Rate Conversion

Processing
- Hardware
  - FPGAs
  - DSPs
  - ASICs
- Software
  - Algorithms
  - Middleware
  - CORBA
  - Virtual Radio Machine

RF/IF
- A/D
- D/A
- Digital Front End

Base Band Processing

ANTENNA

RF
- AMPLIFIER
- FILTER

A/D
- D/A

Modem Error Correction

Encryption

Network Routing GUI

User

HARDWARE

SOFTWARE

Waveform

Control
Software Defined Radio

- Advantages:
  - Flexibility
  - Upgradable
  - Sophisticated processing
  - Ideal Processing chain
  - Not approximate like in analog hardware

- Already used in consumer electronics
  - Cellphone baseband processors
  - Wifi, GPS, etc....
Shameless Plug

- If you are interested in how Analog to digital converters, amplifiers etc...work and how to make them

- Take ESE 568!

- Good to know both sides of the system
Future of ADC design

- Today’s ADCs are extremely well optimized
- For non-incremental improvements, we must explore new ideas in signal processing that tackle ADC inefficiency at the system level
  - Compressed sensing
  - Finite innovation rate sampling
  - Other ideas?
Devised a way to randomly sample 20% of the Nyquist required samples and still detect the tremor frequencies within 100mHz
- Requires post processing to randomly sample!

Implement hardware on chip to “choose” samples in real time
- Only write to memory the “chosen” samples
  - Design random-like sequence generator
- Only convert the “chosen” samples
  - Design low energy ADC
Discrete Time Signals
Signals

- Signals carry information
- Examples:
  - Speech signals transmit language via acoustic waves
  - Radar signals transmit the position and velocity of targets via electromagnetic waves
  - Electrophysiology signals transmit information about processes inside the body
  - Financial signals transmit information about events in the economy
- Signal processing systems manipulate the information carried by signals

**Signal** (n): A detectable physical quantity ...by which messages or information can be transmitted (Merriam-Webster)
Signals are Functions

**Definition**

A **signal** is a function that maps an independent variable to a dependent variable.

- Signal $x[n]$: each value of $n$ produces the value $x[n]$

- In this course, we will focus on **discrete-time** signals:
  - Independent variable is an integer: $n \in \mathbb{Z}$ (will refer to as *time*)
  - Dependent variable is a real or complex number: $x[n] \in \mathbb{R}$ or $\mathbb{C}$

![Graph of a discrete-time signal](image)
A Menagerie of Signals

- Google Share daily share price for 5 months

- Temperature at Houston Intercontinental Airport in 2013 (Celsius)

- Excerpt from Shakespeare’s *Hamlet*
Plotting Signals Correctly

- In a discrete-time signal $x[n]$, the independent variable $n$ is discrete (integer)

- To plot a discrete-time signal in a program like Matlab, you should use the `stem` or similar command and not the `plot` command

- **Correct:**

- **Incorrect:**
Wrap up

- Admin
  - Find web, get text, assigned reading…
  - [http://www.seas.upenn.edu/~ese531](http://www.seas.upenn.edu/~ese531)
  - [https://canvas.upenn.edu/](https://canvas.upenn.edu/)

- Big Ideas/takeaway
  - Analysis of sampled and quantized signals

- Remaining Questions?