Digital Signal Analysis Techniques: Time, Frequency, and Spatial Algorithms

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DIGITAL SIGNAL ANALYSIS TECHNIQUES

TIME, FREQUENCY, AND SPATIAL ALGORITHMS
FOR HIGH RESOLUTION SPECTRAL
ANALYSIS AND TIME SERIES ANALYSIS

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SECTION 1:
Signal Analysis Basics—Signals (real & complex), Transforms, Matrix Algebra

SECTION 2:
Classical Spectral Analysis

SECTION 3:
Parametric Models and Methods for Temporal & Spectral Analysis

SECTION 4:
Autoregressive (AR, maximum entropy) Parametric Analysis
Moving Average (MA) Parametric Analysis, AR-MA Parametric Analysis

SECTION 5:
Exponential Time Series Model (Prony Method)
Least-Squares-Based Sinusoidal Frequency Estimation

SECTION 6:
Minimum Variance (MV) FIR Filtering and Non-Parametric Spectral Analysis
Eigenanalysis and Subspace Approaches to Frequency Estimation

SECTION 7:
Multi-Channel (MC) Temporal and Spectral Analysis

SECTION 8:
Two-Dimensional (2D) Temporal and Spectral Analysis
Spatial Spectral Analysis (Direction of Arrival [DOA] Estimation)

SECTION 9:
Non-Stationary Time vs Frequency Signal Analysis (Linear & Quadratic TFAs)

SECTION 10:
Time-Scale/Multi-Resolution Time vs Frequency Analysis
Deconvolution Techniques

BONUS SECTIONS:
Time Delay Estimation (TDE)
High-Order Spectral (Polyspectral) Analysis (beyond 2nd-order statistics)
SECTION 1: REVIEW OF SIGNAL ANALYSIS TOOLS

- HISTORICAL PERSPECTIVE AND MOTIVATIONS (Chapter 1) *
- SIGNAL REVIEW (source of complex signals)
- SAMPLING REVIEW
- FOURIER & Z TRANSFORMS REVIEW (Chapter 2)
- LINEAR SYSTEMS REVIEW (Chapter 2)
- MATRIX ALGEBRA REVIEW (Chapter 3)
- COURSE TEST DATA SOURCES

* Chapter references are for Marple’s 1987 textbook; copy on your course CD

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CREATING ONE-SIDED COMPLEX DT LOWPASS SIGNALS FROM REAL DT LOWPASS SIGNALS
(DISCRETE-TIME ‘ANALYTIC’ LOWPASS SIGNAL)

- TIME DOMAIN
  - Reilly et al. [November 1994
    IEEE Signal Processing Trans.]
  - approach using all-pass filter
  - with comparable passband ripple
  - as Hilbert Transform approximation filter

- FREQUENCY DOMAIN (3 cases)
  - Standard
    - N-point real x[n] → N-point complex z[n]
    - (same sample rate)
  - Decimated
    - N-point real x[n] → N/2-point complex z[n]
    - (half sample rate)
  - Interpolated
    - N-point real x[n] → MN-point complex z[n]
    - (M times sample rate)

```matlab
function z=analytic(x)
% Creates discrete-time analytic signal from real-valued signal

N=length(x); % x -- input vector of real data samples
z=fft([x;zeros(N/2-1,1)]); % z -- output vector of complex data samples
```

Paper reference on course CD-R

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SECTION 2: CLASSICAL SPECTRAL ANALYSIS

- REVIEW OF RANDOM VARIABLES & PROCESSES
- CORRELATION
- SPECTRAL DENSITY
- WINDOWING
- ESTIMATION APPROACHES
  - Correlogram
  - Periodogram
  - Blackman-Tukey

**Chapters 4 and 5 of 1987 text**
SECTION 3: PARAMETRIC METHODS OF SPECTRAL ANALYSIS

Parametric = data -> parameters -> spectrum & correlation
Nonparametric = data -> spectrum & correlation

- PARAMETRIC TIME SERIES MODELS (Chapter 6)
- RELATIONSHIPS AMONG AR, MA, ARMA MODELS (Chapter 6)
- PARAMETRIC MODEL AUTOCORRELATION RELATIONSHIPS
- AUTOREGRESSIVE PROCESS PROPERTIES (Chapter 7)

Linear Prediction Parametric Model, Lattice Parametric Model

THREE EQUIVALENT AR(p) [All-Pole] MODEL REPRESENTATIONS

FAST ALGORITHM LINKS

All representations require exactly $p + 1$ parameters II
SECTION 4: AUTOREGRESSIVE / MOVING AVERAGE/ARMA ESTIMATIONS

- AR SPECTRAL ESTIMATION (Chapter 8)
- MA SPECTRAL ESTIMATION (Chapter 10)
- ARMA SPECTRAL ESTIMATION (Chapter 10)

MODIFIED COVARIANCE AR SPECTRAL DENSITY EXAMPLE: WHALE DATA
SECTION 5: EXPONENTIAL TIME SERIES AND ADAPTIVE FILTER SPECTRAL ESTIMATION

- DAMPED EXPONENTIAL PARAMETER ESTIMATION (Chapter 11)
- RELATIONSHIP TO AUTOREGRESSIVE PSD
- MODIFIED LEAST SQUARES PRONY ALGORITHM
- MINIMUM VARIANCE SPECTRAL ESTIMATION (Chapter 12)

PRONY ENERGY SPECTRAL DENSITY ESTIMATION DEMONSTRATION: RADAR DATA
SECTION 6: EIGENANALYSIS -- BASED FREQUENCY ANALYSIS

- EIGENANALYSIS TECHNIQUES (Chapter 13)
  - Signal and Noise Subspaces
  - Noise Reduced AR and Minimum Variance
  - Noise Excision Prony
  - MUSIC Frequency Estimation
  - Pisarenko Harmonic Decomposition
  - ESPRIT Algorithm

Find frequencies by:
1. search for plot peaks
2. polynomial factoring
3. direct computation

FORWARD PREDICTION

BACKWARD PREDICTION
SECTION 7: MULTI-CHANNEL TEMPORAL AND SPECTRAL ANALYSIS

- MULTICHANNEL SPECTRAL ANALYSIS (Chapter 15)

  One demo script: `spectrum_demo_MC`

  <> Periodogram
  <> Blackman-Tukey
  <> Four AR Algorithms (YW, Lattice[Burg, Geo], Covar)
  <> Minimum Variance

TWO - CHANNEL AUTOREGRESSIVE ANALYSIS OF SUNSPOT AND TEMPERATURE DATA

NUTTALL - STRAND AR (25)

(a) Autospectrum of filtered sunspot numbers
(b) Autospectrum of filtered temperature data
(c) Magnitude squared coherence between chs.
(d) Phase of coherence (proportional to time lag between time series)

SINGLE - CHANNEL BURG AR (25)

(a) Autospectrum of filtered sunspot numbers
(b) Autospectrum of filtered temperature data
SECTION 8: MULTI-DIMENSIONAL TEMPORAL AND SPECTRAL ANALYSIS

- TWO-DIMENSIONAL SPECTRAL ANALYSIS (Chapter 16)
  One demo script: `spectrum_demo_2D`
  - Periodogram
  - Blackman-Tukey
  - Four AR Algorithms (YW, Lattice, Covar, Modcovar)
  - Minimum Variance

- SPATIAL SPECTRAL ANALYSIS (DOA ANALYSIS)
SESSION 10: MULTI-RESOLUTION and TIME-SCALING ANALYSIS TECHNIQUES

- TIME-SCALE REPRESENTATIONS (TSRs) (Wavelets)
- MULTI-RESOLUTION FOURIER SIGNAL ANALYSIS

**MRFT* TFA GRAM: EuroCopter**

- Short – Term Fourier Transform
- Long – Term Fourier Transform
- Wavelet Transform (1/24 octave spacing)
- * Multi-Resolution Fourier Transform

HELI-COPTER DOPPLER RADAR TFA GRAM
(a) UNIFORM RESOLUTION SFFT GRAM (Short Window)
(b) UNIFORM RESOLUTION SFFT GRAM (Long Window)
(c) LOGARITHMIC TIME-RESOLUTION WT GRAM
(d) MULTI-RESOLUTION WRT GRAM

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