Spring 2003

CE 200: Engineering Data Analysis

Instructor: Henri Gavin, 122 Hudson Hall, `Henri.Gavin@Duke.edu`
Class Time: Tu, Th, 12:40–1:55, Room 115A Hudson, ACES Call # 13335
Office Hours: We 1:30 – 2:30 and by appointment
Textbooks:
- Bendat, Julius S., and Piersol, Allan G., *Random Data: Analysis and Measurement Procedures,* 2nd ed., Wiley-Interscience, 1986.
- Press, W.H., Teukolsky, S.A., Vetterline, W.T., and Flannery, B.P., *Numerical Recipes in C: The Art of Scientific Computing,* 2nd ed., Cambridge University Press, 1992. (also, `http://www.nr.com/`)

T.A.: Cenk Alhan, 053 Engineering Annex, `Cenk.Alhan@Duke.edu`
Website: `http://www.duke.edu/~hpgavin/ce200/`
Prerequisite: Graduate standing or permission of instructor.
Computers: Many assignments will require computations using Matlab. Students are responsible for familiarizing themselves with Matlab.
Grading: Homeworks(6) 30%; Exams(2): 30%; Final Project(1): 30%; Presentation: 10%

Bulletin Description:

CE 200. Engineering Data Analysis. Introduction to the statistical error analysis of imprecise data and the estimation of physical parameters from data with uncertainty. Interpolation and filtering. Data and parameter covariance. Emphasis on time series analysis in the time- and frequency-domains. Linear and nonlinear least squares. Confidence intervals and belts. Hypothesis testing. Introduction to linear and nonlinear estimation of dynamic systems in engineering. Prerequisite: graduate standing or permission of instructor. Instructors: Boadu or Gavin. One course.

Course Schedule:

Week	*Dates*	*Topic*
1	Jan.8–Jan.17	Review of engineering statistics *references:* [23, 27, 31, 38, 42]
2	Jan.20–Jan.24	Sample covariance and correlation matrices: computation and interpretation *references:* [13, 23, 27, 31, 42]
3	Jan.27–Jan.31	Time series analysis: ensembles, auto-correlation and cross-correlation *references:* [1, 6, 34, 46]
4	Feb.3–Feb.7	Spectral analysis: Fourier transforms, spectra and transfer function estimates *references:* [6, 37, 39, 48, 55]
5	Feb.10–Feb.14	Time-frequency analysis: analytic signals and wavelets *references:* [14, 37]
6	Feb.17–Feb.21	Least Squares: weighted residuals and linearity in the parameters *references:* [5, 7, 24, 31, 37]
7	Feb.24–Feb.28	Linear regressions for polynomial, power-law, and ARMA models, RLS *references:* [6, 7, 30, 37]
8	Mar.3–Mar.7	Error propagation, estimation of parameter uncertainty, confidence bands *references:* [15, 24, 37, 42, 47]
9	Mar.10–Mar.14	*Spring Break*
10	Mar.17–Mar.21	Condition number, null spaces, and introduction to singular value decomposition *references:* [24, 37]
11	Mar.24–Mar.28	Scaling and orthogonal polynomials in linear least squares *references:* [22, 37]
12	Mar.31–Apr.4	Constrained nonlinear least squares using Nedler-Mead simplex and BFGS methods *references:* [3, 5, 10, 37]
13	Apr.7–Apr.11	Linear and nonlinear estimation of dynamic systems in engineering *references:* [3, 20, 30]
14	Apr.14–Apr.18	Project presentations

DETAILED OUTLINE

1. **Review of engineering statistics:**

   accuracy and precision of measured quantities; statistical description of data; random variables; discrete and continuous probability density functions; samples, sets and populations; common probability density functions and their properties; functions of independent random variables; the central limit theorem; joint probability density functions; marginals; covariance and correlation; functions of correlated random variables.
   MATLAB: `normpdf`, `lognpdf`, `normcdf`, `normplot`, `cdfplot`, `norminv`, `rand`, `randn`, `disttool`, `polytool`

2. **Sample covariance and correlation matrices:**

   Chebyshev's theorem and Chauvenet's Criterion for out-lying data. Computation of covariance and correlation from repeated samples and from known a priori sensor knowledge. Resampling statistics. Definiteness and convergence.

3. **Time series analysis:**

   ensembles, stationarity and ergodicity; auto-correlation and cross-correlation.

4. **Spectral analysis:**

   the Fourier transform and the fast Fourier transform (FFT); leakage and resolution; signal processing using the FFT, filtering and integration; power spectrum estimation, windows and averaging; effects of noise on inputs and outputs; H_1, H_2, H_v transfer function estimates; coherence estimates.

5. **Time–frequency analysis:**

   the analytic signal; Hilbert transforms and Kramer-Leadbetter envelopes; phase velocity; time-frequency distributions, Choi-Williams kernels; wavelets

6. **Linear least squares:**

   χ^2 and other goodness of fit criteria; dependent and independent variables; interpolating, smoothing, and de-trending data; linearity in the parameters, nonlinear models and linear least squares formulations.

7. **Linear regressions:**

   power polynomials and power-laws; auto-regressive, moving average models, z-transform, poles & zeros, linear prediction and recursive least squares; forgetting factors; linear prediction and system identification.

8. **Error propagation:**

   data covariance and parameter covariance; Student-t confidence intervals, confidence ellipsoids and confidence bands.

9. **Condition number, null spaces, and introduction to singular value decomposition:**

   random and bias errors; null spaces; regularization and series truncation.

10. **Scaling and orthogonal polynomials:**

    re-scaling relationships for power polynomial curve-fits; minimization of the condition number; continuous and discrete Chebyshev, Legendre and Forsythe polynomials; interpolation points; recurrence relationships.

11. **Constrained nonlinear least squares using Nedler-Mead simplex and BFGS:**

    the simplex; Nedler-Mead rules for simplex evolution; annealing; penalty function for constraints; Lagrange multipliers; Gradient calculation and Hessian update formula; examples.

12. **Linear and nonlinear estimation of dynamic systems in engineering:**

    static and dynamic models; models for hysteresis, chatter and dynamic buckling; curve-fitting frequency response functions; parameter estimation from curve-fitting; nonlinear dynamic systems and identification.

13. **Individual projects:**

    identification of project topic; preliminary analysis incorporating equilibrium, continuity, balance laws and material characteristics; interactions between test specimens, sensors, and test hardware; development of simulations; calibration and data collection; parameter estimation and error analysis; oral presentation and written report.

REFERENCES

[1] Anderson, T.W., *The Statistical Analysis of Time Series,* John Wiley and Sons, 1971.

[2] Baird, D.C., *Experimentation: An Introduction to Measurement Theory and Experiment Design,* 3rd ed. Prentice Hall, 1994.

[3] Bard, Yonathan, *Nonlinear Parameter Estimation,* Academic Press, 1974.

[4] Barford, N.C., *Experimental Measurements: Precision, Error and Truth,* 2nd ed. John Wiley, 1985.

[5] Beck, James V. and Arnold, Kenneth J., *Parameter Estimation in Engineering and Science,* John Wiley & Sons, 1977.

[6] Bendat, Julius S., and Piersol, Allan G., *Random Data: Analysis and Measurement Procedures,* 2nd ed. Wiley-Interscience, 1986.

[7] Bevington, Philip R. and Robinson, D. Keith, *Data Reduction and Error Analysis for The Physical Sciences,* McGraw-Hill Higher Education, 1992.

[8] Björck, Âke, *Numerical methods for least squares problems,* Society for Industrial & Applied Mathematics, 1996.

[9] Box, George E.P., Hunter, J. Stuart and Hunter, William G., *Statistics for Experimenters: An Introduction to Design, Data Analysis, and Model Building,* John Wiley & Sons, 1978.

[10] Brent, Richard P., *Algorithms for Minimization Without Derivatives,* Dover Press, 2000.

[11] Bury, Karl, *Statistical Distributions in Engineering,* Cambridge University Press, 1999.

[12] Cadzow, James A., "Least Squares, Modeling, and Signal Processing," *Digital Signal Processing,* vol. 4 (1994) pp. 2–20.

[13] Clifford, A.A., *Multivariate Error Analysis,* John Wiley & Sons, 1973.

[14] Cohen, Leon, *Time-Frequency Analysis,* Prentice Hall Signal Processing Series, 1995.

[15] Coleman, Hugh, W., and Steele, W. Glenn, *Experimentation and Uncertainty Analysis for Engineers,* 2nd ed. John Wiley and Sons, 1999.

[16] Cowan, Glen, *Statistical data analysis,* Oxford University Press, 1998.

[17] Daniel, Cuthbert, Wood, Fred S. and Gorman, John Wayne, *Fitting Equations to Data: Computer Analysis of Multifactor Data,* 2nd Ed. John Wiley & Sons, 1999.

[18] Deming, W. Edwards, *Statistical Adjustment of Data,* Dover Press, 1984.

[19] Dorf, Richard C., (Editor) *The Engineering Handbook,* CRC Press, 2000. `http://www.duke.edu/~hpgavin/ce200/CRC-EngHndbk.html`

[20] Ewins, D.J., *Modal Testing: Theory, Practice, and Application,* 2nd edition. Research Studies Press, 1998.

[21] Hardin, Jay C., *Introduction to Time Series Analysis,* National Aeronautics and Space Administration, Reference Publication 1145, November 1990.

[22] Hamming, R.W., *Numerical Methods for Scientists and Engineers,* 2nd ed., Dover Publications, 1973.

[23] Havlicek, Larry L. and Crain, Ronald D., *Practical Statistics for the Physical Sciences,* American Chemical Society Press, 1988.

[24] Hofmann, Bernd, *Regularization for Applied Inverse and Ill-Posed Problems,* Teubner-Texte zur Mathematik; 85, Liepzig, 1986.

[25] James, J.F., *A Student's Guide to Fourier Transforms: With Applications in Physics and Engineering,* Cambridge University Press, 1995.

[26] Johnson, C. Richard, Jr., *Lectures on Adaptive Parameter Estimation,* Prentice-Hall, 1988.

[27] Lapin, Lawrence *Probability and Statistics for Modern Engineering,* Brooks/Cole 1983.

[28] Lawson, Charles L. and Hanson, Richard J., *Solving Least Squares Problems,* (Classics in Applied Mathematics, No 15) Society for Industrial & Applied Mathematics, 1995.

[29] Levenberg, Kenneth, "A Method for the Solution of Certain Non-Linear Problems in Least Squares," *Quart. Applied Mathematics,* Vol II, no 2, (1944) pp. 164–167.

[30] Ljung, Lennart, and Söderström, Torsten, *Theory and Practice of Recursive Identification,* MIT Press, 1983.

[31] Mandel, John, *The Statistical Analysis of Experimental Data,* Dover Press, 1990.

[32] Marquardt, Donald W., "An Algorithm for Least-Squares Estimation of Nonlinear Parameters," *J. Society for Industrial and Applied Mathematics,* vol. 11, no. 2, (1963) pp: 431–441.

[33] Meeker, William Q. and Escobar, Luis A., *Statistical Methods for Reliability Data,* Wiley-Interscience,

[34] Middleton, Gerard V., *Data Analysis in the Earth Sciences Using Matlab,* Prentice Hall, 1999.

[35] Montgomery, Douglas C., *Design and Analysis of Experiments, 5th Edition,* John Wiley & Sons, 2000.

[36] Morris, Alan S., *The Essence of Measurement,* Prentice Hall, (Essence of Engineering Series) 1996.

[37] Press, W.H., Teukolsky, S.A., Vetterline, W.T., and Flannery, B.P., *Numerical Recipes in C: The Art of Scientific Computing,* 2nd ed., Cambridge University Press, 1992.

[38] Rabinovich, Seymon and Alferieff, M. E. (Translator) *Measurement Errors and Uncertainties: Theory and Practice,* 2nd ed. American Institute of Physics, 1999.

[39] Ramirez, Robert W., *The FFT: Fundamentals and Concepts,* Prentice Hall, 1985.

[40] Ray, Martyns, *Engineering Experimentation: Ideas, Techniques and Presentation,* McGraw Hill, 1988.

[41] Robinson, Enders A., *Least Squares Regression Analysis in Terms of Linear Algebra,* Goose Pond Press, Houston Texas, 1981.

[42] Sachs, Lothar *Applied Statistics: A Handbook of Techniques,* Springer-Verlag, 1982.

[43] Schenck, Hilbert, *Theories of Engineering Experimentation,* 3rd ed., McGraw Hill, 1979.

[44] Schoukens, J. and Pintelon, R., *Identification of Linear Systems — A Practical Guide to Accurate Modeling,* Pergamon Press, 1991.

[45] Skoglund, Victor J. *Similitude: theory and applications,* International Textbook Co. 1967.

[46] Solnes, Julius, *Stochastic Processes and Random Vibration – Theory and Practice,* John Wiley, 1997.

[47] Taylor, John R., *An Introduction to Error Analysis: The Study of Uncertainties in Physical Measurements,* 2nd ed. University Science Books, 1997.

[48] Trefethen, Lloyd N., *Spectral Methods in MATLAB,* Society for Industrial and Applied Mathematics, 2001.

[49] Wall, Francis J., *Statistical data analysis handbook,* McGraw-Hill, c1986.

[50] Webster, John G., (Editor) *The Measurement, Instrumentation, and Sensors Handbook,* CRC Press, 1998. `http://www.duke.edu/~hpgavin/ce200/CRC-MsmntHndbk.html`

[51] Wheeler, Anthony J., and Ganji, Ahmad R., *Introduction to Engineering Experimentation,* Prentice Hall, 1996.

[52] Wilson, E. Bright, *An Introduction to Scientific Research,* Dover Press, 1990.

[53] Wright, Charles P., *Applied Measurement Engineering,* Prentice-Hall, 1995.

[54] Youden, W. J., *Experimentation and Measurement,* Dover Press, 1998.

[55] Zonst, Anders E., *Understanding the FFT: A Tutorial on the Algorithm and Software for Laymen, Students, Technicians and Working Engineers,* Citrus Press, 1995.