SYLLABI OF SHMC RELATED COURSES

EMI SHM&C Committee

Course Title: Structural Health Monitoring

University/Institute: Princeton University

Instructor: Branko Glisic

Course Introduction: Needs for optimization of maintenance costs, increase of safety, and continuous developments of new construction materials and methods, as well as recent technological developments in various branches of science and engineering led to creation of this relatively new, interdisciplinary branch of engineering – Structural Health Monitoring. This course introduces the topics with basic definitions of measurement and monitoring, monitoring activities and entities, and with various available and emerging monitoring technologies. The fundamental criteria for applications on concrete, steel and composite materials are elaborated, and basics on data interpretation and analysis for both static and dynamic monitoring are presented. Finally, methods applicable to large spectrum of civil structures, such as bridges, buildings, geo-structures, and large structures are developed. Each lecture of the course is illustrated with examples taken from the practice. The course is offered to both graduate students and undergraduate students of higher years (juniors and seniors). A fair knowledge in Construction Materials, Structural Analysis, and Engineering Mathematics is expected from participants.

Syllabus:
1. Introduction to structural health monitoring**:** basic notions, needs, and benefits; smart/intelligent structures.
2. The structural health monitoring process**:** core activities and entities (actors); example of structural health monitoring project.
3. Monitoring systems**:** basic notions on measurement; requirements and available technologies; classification of deformation sensors by gage-length; static and dynamic monitoring.
4. Deformation sensors**:** sensor gage-length and measurement; short-gage vs. long-gage sensors; determination of gage-length limits; distributed sensors; tilt-meters; displacement sensors.
5. Strain and deformation components**:** strain components and strain time evolution; elastic and plastic (structural) strain; thermal strain, creep, and shrinkage.
6. Interpretation of measurements**:** sources of errors; determination of strain components and stress from strain measurement; detection of anomalous structural condition – model-based and model-free approaches.
7. Dynamic monitoring**:** sources of dynamic behavior; accelerometers; handling and storage of data; sampling frequency and aliasing; system identification and modal analysis.
8. Global and integrity monitoring**:** introduction to global monitoring concept; simple, parallel, crossed, and triangular topologies; integrity monitoring.
9. SHM strategies 1**:** monitoring of bridges – simple beam, continuous girder, arch, cable stayed, and suspension bridge.
10. SHM strategies 2**:** monitoring of pile foundations; monitoring of buildings; monitoring of heritage structures.
11. SHM strategies 3**:** monitoring of dams, tunnels, and pipelines.
12. Monitoring other parameters**:** corrosion, fatigue, humidity and pH of concrete, weather, etc.

Course References:

1. *Glisic, B. and Inaudi, D,* Fibre Optic Methods for Structural Health Monitoring, John Wiley & Sons, Inc., 2007, ISBN 978-0-470-06142-8

Course Title: System Identification

University/Institute: Duke University

Instructor: Henri Gavin

Course Overview: System Identification is the process of relating the reality of measured data sets to the idealization of mathematical models. Identified models reveal the phenomenae and processes at work within actual systems and are useful in predicting system responses, designing system controllers, and quantifying uncertainties. Models considered in this course take the form of systems of ordinary differential equations. Recent advances in subspace methods for system identification provide a means to estimate high dimensional linear state-space realizations from sparse noisy measurements of input-output data (or output-only data) via a QR decomposition and an SVD decomposition of Hankel matrices of the data. Subspace methods are direct in the sense that they do not require an initial guess of a canonical model, or the model order, or a convergent iterative algorithm. The course will start with a review of some tools of numerical linear algebra, the formulation of ordinary and total least squares problems, and projections of linear vector spaces. These tools will then be applied to the estimation of state-space models via eigensystem realization and subspace ID.

Syllabus:
1. Nonlinear Constrained Optimization, in general: Least squares and Levenberg-Marquardt; Nelder-Mead; KKT and Sequential Quadratic Programming; error propagation. ℓ_2 regularization and ℓ_1 regularization as a QP, Prony series.
2. Matrix Decompositions: linear vector spaces, Householder and QR decomposition; singular value decomposition; truncation.
3. Total Least Squares, Singular Spectrum Analysis: Eckart-Young theorem, total least squares, and structured total least squares; orthogonal and oblique projections; filtering via rank-reduced Hankel matrices.
4. Discrete-time state-space models: impulse response, convolution and frequency response; Kalman filter; controllability, observability, and gramians; Lyapunov equations, balanced realizations, and model reduction. MIMO Wiener filters and recursive least squares.
5. Eigensystem Realization with Kalman Observer: Hankel matrices of Markov parameters; system and observer Markov parameters; the eigensystem realization algorithm; OKID, modal analysis, Hankel singular values and stochastic OKID.
6. Subspace Identification: input, output, and state matrices; persistent disturbance and subspace intersections; orthogonal and oblique projections via LQ decomposition; deterministic subspace id (N4SID, MOESP); stochastic subspace id (CVA, CCA).
7. Applications / Projects: possibly including real measurements from laboratory or field experiments.

Course References:

1. *Katayama, Tohru*, Subspace Methods for System Identification, Springer, 2005
2. *Van Overschee, Peter, and De Moore, Bart,* Subspace Identification for Linear Systems, Kluwer, 1996.
3. *Juang, Jer-Nan,* Applied System Identification, Prentice Hall, 1994.

Course Title: Random Vibrations

University/Institute: Georgia Institute of Technology

Instructor: Yang Wang

Course Overview: This course introduces concepts of random processes for modeling dynamic structural behavior under time-dependent excitations. Numerical tools will be provided for assessing the reliability of structural systems subject to uncertain dynamic loads. Both single and multiple degree-of-freedom structures will be studied. The course also presents experimental modal analysis of structures with random vibration data.

Syllabus:

1. Introduction; review of basic probability theory – sample space, probability axioms and basic laws, conditional probability and Bayes rule
2. Independence, discrete and continuous random variables, functions of a random variable
3. Two random variables, joint, marginal, and conditional distributions; functions of two random variables, expectation, moments
4. Covariance, correlation, conditional expectation, iterated expectation
5. Mean square error estimation, linear estimation, jointly Gaussian random variables
6. Random vectors, joint, marginal, and conditional CDF, PDF, PMF, mean and covariance matrix, Gaussian random vectors
7. Random processes, IID processes, random walk, Markov processes, Gauss-Markov process
8. Mean and autocorrelation functions, Gaussian random processes, stationary random processes, strong and weak stationarity
9. Autocorrelation functions, power spectral density
10. Response of LTI system to WSS process input, output mean, autocorrelation, and PSD
11. Random vibrations of SDOF systems, white noise excitations
12. Random vibrations of MDOF systems, proportional and non-proportional damping
    Lab Demo - Acceleration measurement of a laboratory MDOF structure using wireless sensors
13. Threshold crossings, reliability by first passage time, envelop process, distribution of extrema
14. Experimental modal analysis: natural excitation technique (NExT) and eigen-system realization (ERA)
15. Recursive estimation, posterior PDF, condition PDFs for Gaussians, information interpretation
16. Kalman filter, LTI system with sensor noise, Lyapunov recursion, measurement update, time update, steady-state Kalman filter

Course References:

1. *L. D. Lutes and S. Sarkani,* Random Vibrations: Analysis of Structural and Mechanical Systems.
2. *P. H. Wirsching, T. L. Paez, and K. Ortiz,* Random Vibrations, Theory and Practice.
3. *Alberto Leon-Garcia*, Probability, Statistics, and Random Processes for Electrical Engineering.

Course Title: Advanced Dynamics and Smart Structures

University/Institute: Georgia Institute of Technology

Instructor: Yang Wang

Course Overview: This course gives an overview of emerging technologies in advanced dynamics and smart structures. Topics include frequency response of single and multiple DOF structures, applications of Fourier transform and Laplace transform in structural dynamics, numerical techniques for signal processing and modal analysis, smart wireless sensor technologies for structural monitoring, as well as structural control technologies (e.g. base isolation, tuned mass damper, semi-active damper). The course can assist CEE graduate students in quickly grasping both theoretical fundamentals and numerical techniques needed for in-depth analysis in structural dynamics. The course also helps to broaden students' view with latest advancements in structural health monitoring and control technologies.

Syllabus:
1. Introduction to sensors, data acquisition, and actuation
2. Fourier series and Fourier transform
3. Vibration transfer function of undamped and damped SDOF systems
4. Impulse response and convolution for a SDOF system
5. Free vibration of MDOF systems (undamped and non-proportional viscous damping)
6. Frequency response / transfer function matrix of MDOF systems
7. From continuous to discrete: impulse-train sampling, signal reconstruction, aliasing
8. Discrete Fourier transform and convolution in discrete domain
9. Experimental modal analysis: peak picking
   Lab Demo - Acceleration measurement of a laboratory MDOF structure using wireless sensors
   Field Demo - Field instrumentation of wireless accelerometers (MARC Bridge or Bobby Dodd Stadium)
10. Linear algebra review
11. Laplace transform and applications to free and forced vibrations of SDOF systems
12. Laplace transform and applications to free and forced vibrations of MDOF systems
13. Discrete-time linear dynamical systems
14. Singular value decomposition
15. Experimental modal analysis: eigensystem realization algorithm
16. Concepts and examples of passive, semi-active, and active structural control

Course References:
1. *Maia and Silva,* Theoretical and Experimental Modal Analysis.
2. *Oppenheim, Willsky, and Nawab,* Signals & Systems.
3. *Chopra,* Dynamics of Structures.

Course Title: Structural Health Monitoring

University/Institute: Clemson University

Instructor: Sez Atamturktur

Course Objectives: This course examines the use of low-cost, long term monitoring systems to keep civil infrastructure under constant surveillance, ensuring structural integrity. Moreover, the tools and skills the students will learn in this class can be implemented to develop sustainable maintenance and rehabilitation schemes and programs. The course covers the concepts of rapid after disaster assessment of civil infrastructure. The tools and skills incorporated within the curriculum of this class provide quantitative means to assess the structural integrity loss a system undergoes after natural disasters and other hazardous events.

Syllabus:

1. Course Introduction, SHM introduction
2. Brief History of SHM, Operational Evaluation
3. Case Studies Relevant to Structural Sustainability
4. Case Studies Relevant to Structural Resiliency
5. SHM Procedure
6. Brief Overview of Structural Dynamics
7. Operational evaluation of the structure
8. Experimental Modal Analysis (input-output modal analysis)
9. Operational Modal Analysis (output only modal analysis)
10. Data acquisition
    a. Obtaining useful measurements
    b. Excitation
    c. Sensing
    d. Data transmission
    e. The coherence function
11. Signal Processing Basics
12. Feature extraction
13. Data Normalization
14. Rapid Damage Detection (Resiliency) & Long Term Periodic Monitoring (Sustainability)
    a. Data-based: Statistical model development
    b. Model-based: Finite Element model updating
15. Student Class Projects (a discussion on how they relate to sustainability and resiliency)

Course Title: Sensors, Electrical Circuits, and Signal Processing

University/Institute: University of Michigan

Instructor: Jerome P. Lynch

Course Overview: This course introduces students to the fundamentals of collecting and processing experimental data for civil and environmental applications. The course begins with an introduction to DC and AC circuits followed by the coverage of sensors used in the civil and environmental field. Examples and hands-on demonstrations will be presented relevant to seismic, environmental, structural and hydraulic monitoring.

Syllabus:
1. Introduction, Electric Circuit Variables
2. Circuit Elements: Non-energy storage; Transistors and Transducers
3. Analyzing Resistive Circuits: Kirchhoff's Laws; Parallel and Series Elements
4. Source Transformations
5. Operational Amplifier
6. Energy Storage Elements; Switched Circuits; Mathematical Operations with Circuits
7. Response of RC and RL Circuits; Stability and Differential Operators via RC and RL Circuits
8. Circuit Response of RLC Circuits
9. AC Circuits: Sinusoidal Behavior; Phasors and Complex Impedance; Kirchhoff's Laws
10. Power; Transformers
11. Data Acquisition System Basics
12. Sensor Characteristics
13. Analog Interface Circuits; Digital Interface Circuits
14. Strain Gages
15. Fiber Optic Strain Gages
16. Load Cells
17. Position Sensors
18. Geophone Sensors
19. Accelerometers
20. Pressure Sensors
21. Flow Sensors
22. MEMS and Advanced Fabrication

Textbooks:
1. *R. C. Dorf and J. A. Svoboda*, Introduction to Electric Circuits, Wiley, 2010 – 8th Edition.
2. *J. Fraden*, Handbook of Modern Sensors, Springer, 2010 – 4th Edition.

Course Title: Dynamical Infrastructure Systems

University/Institute: University of Michigan

Instructor: Jerome P. Lynch

Course Overview: This course is an introductory course in the fundamentals of dynamics system theory applied to infrastructure systems including applications in modeling, monitoring and controlling structural, transportation, hydraulic, and electrical grid systems. Linear systems are emphasized including continuous-time and discrete-time systems but elementary concepts in nonlinear systems are also presented. Additional topics include feedback control theory, system identification, and cyber-physical system architectures.

Syllabus:
1. Introduction to Dynamics
2. Introduction to System Types
3. Single Variable Differential Equations for Continuous Time Systems
4. Difference Equation Models for Discrete Time Systems
5. Realization of Dynamical Systems
6. Convolution and the Laplace Transform for Continuous Time Systems; Dynamic Response of SISO Systems by the Laplace Transform
7. Complex Plane and the Behavior of SISO Dynamic Systems
8. Block Diagrams for Dynamic Systems
9. Feedback Control of Dynamical Systems
10. Introduction to Multivariable Systems
11. Homogeneous and Particular Solutions to MIMO Systems
12. Fourier Transform: Introduction and Applications
13. Correlation and Spectral Analyses of Random Signals
14. Introduction to Digital Systems
15. Z-transform and its Applications; Z-Plane and Continuous to Discrete Time Conversion
16. Discrete Fourier Transform
17. Aliasing and Other Signal Issues
18. Data Acquisition and Observation
19. Introduction to Estimation

Text and Reference Books:

1. *Robert H. Jr. Cannon*, Dynamics of Physical Systems, Dover Press, 2003. (Textbook)
2. *David G. Luenberger*, Introduction to Dynamic Systems: Theory, Models, and Applications, Wiley, 1979.
3. *John L. Casti*, Linear Dynamical Systems, Academic Press, 1987.
4. *Michel Verhaegen and Vincent Verdult*, Filtering and System Identification: A Least Squares Approach, Cambridge Press, 2007.

Course Title: Structural Health Monitoring

University/Institute: Tufts University

Instructor: Babak Moaveni

Course Overview: Introduction to vibration-based structural health monitoring including system identification of linear systems. Topics in data acquisition, signal processing, modal identification, parameter estimation, and optimization will be covered.

Syllabus:

1. Introduction: SHM vs NDE, Motivation
2. Sensors, DAQ
3. Signal Processing: FT, PSD, Filters
4. Linear system basics
5. System Identification
    a. Peak picking
    b. ARX models
    c. State space models
    d. ARX to state space
    e. Modal parameters in state space and ARX models
    f. Impulse response
    g. Time Discretization
    h. ERA
    i. NExT
6. Damage identification
    a. FE model updating: Objective function; Residuals; Optimization; Analytical Sensitivity; Regularization
    b. Substructuring
    c. Damage functions

Course Title: Identification Methods for Structural Systems

University/Institute: ETH Zurich

Instructor: Eleni Chatzi and Vasilis Dertimanis

Course Overview: This course will present methodologies for defining a structural system, and assessing its condition based on structural response data. This data is made available via measurements, which are nowadays available from low-cost and easily deployed sensor technologies. The course will explain how engineers may exploit technology for designing and maintaining a safe and resilient infrastructure.

This course aims at providing a graduate level introduction into the modeling and identification of structural systems. The goal is to establish relationships governing the system behavior and to identify the characteristics (mechanical, geometrical properties) of the system itself, based on noisy or incomplete measurements of the structural response.

The course will include theory, as well as laboratory and actual-scale structural testing, thereby offering a well-rounded overview of the ways in which we may extract response data from structures.

Syllabus:
1. Introduction: Background and Motivation
2. Theory of Vibrations
3. Frequency Domain
4. Multiple Degree of Freedom Systems, State Space Models, Eigenvalue Problem
5. Fundamentals of Signal Processing
6. Autoregressive Models (ARMA and ARX)
7. Luenberger Observer, Kalman Filter
8. Eigensystem Realization Algorithm, Natural Excitation Technique
9. Peak Picking, Frequency Domain Decomposition
10. Field experiment using wireless sensors

Suggested Reading:
1. *T. Soderstrom and P. Stoica*, System Identification, Prentice Hall International.
2. http://faculty.uml.edu/pavitabile/22.515/ME22515_PDF_downloads.htm

Course Title: Modeling and Identification in Structural Dynamics

University/Institute: Bogazici University

Instructor: Hilmi Lus

Course Description: This course covers basic formulations in structural dynamics, time and frequency domain models. The identification problem, output and equation error approaches, least squares, state space formulations, subspace methods, and physical parameter estimation.

Syllabus:

1. Forward Problem: Analysis of SDOF systems, time domain and frequency domain solutions, Laplace transform and the transfer function
2. Analysis of MDOF systems, eigenvalues and eigenvectors, classical and non-classical damping
3. Mathematical Preliminaries and Basic Identification Problem: Least squares, Moore-Penrose pseudoinverse, singular value decomposition
4. Equation error formulation for second order systems, numerical integration, effect of noise on identified parameters
5. Time series models, ARX models
6. State Space Formulation: Continuous and discrete time formulations, Complex modal parameters, Markov parameters
7. Minimal Realization Theory, Eigensystem Realization Algorithm, Obtaining Markov parameters, Truncation errors and effects of noise
8. Second Order Parameters Obtained from State Space Models: Collocation and sensor – actuator requirements, Modal parameters from identified complex eigenvalues and eigenvectors, Full order models, Reduced order models

Course References:

1. *L. Meirovıtch*, Fundamentals of Vibrations, McGraw Hill.
2. *D. J. Ewins*, Modal Testing: Theory and Practice, Research Studies Press.
3. *L. Ljung*, System Identification: Theory for the User, Prentice Hall.
4. *J. -N. Juang,* Applied System Identification, Prentice Hall.

Course Title: Structural Health Monitoring

University/Institute: Bogazici University

Instructor: Serdar Soyoz

Course Description: This course covers the basics of structural dynamics, Fourier series and analysis, signal processing, modal parameter estimation in frequency domain, random vibration concepts such as auto-correlation and power spectral density functions, system identification in time domain, finite element model updating, hardware and software applications in structural health monitoring, and real-world examples.

Syllabus:

1. Introduction, Review of Structural Dynamics, SDOF systems, MDOF systems
2. System Identification in Frequency Domain: Fourier Analysis, Signal Processing, Modal Parameter Estimation, Random Vibrations
3. System Identification in Time Domain
4. Finite Element Model Updating
5. SHM Applications
6. Literature Discussion

Course References:

1. *D. J. Inman*, Engineering Vibrations, 2009.
2. *A. K. Chopra*, Dynamics of Structures, 2012.
3. *J. S. Bendat and A. G. Piersol*, Engineering Applications of Correlation and Spectral Analysis, 1993.
4. *D.E. Newland*, An Introduction to Random Vibrations, Spectral and Wavelet Analysis, 2005.
5. *D. J. Ewins*, Modal Testing: Theory, Practice and Application, 2000.
6. *C. Rainieri and G. Fabbrocino*, Operational Modal Analysis of Civil Engineering Structures, 2018.

Course Title: Special Topics in Earthquake Engineering: Introduction to Structural Monitoring and Data Analysis

University/Institute: Bogazici University

Instructor: Erdal Safak

Course Objective: To present the basics on structural health monitoring (i.e., continuous monitoring of the dynamic motions of structures) and data analysis, including selection of sensor types and locations, dealing with noise in digital data, spectral analysis, system identification in time and frequency domains, and damage detection.

Syllabus:
1. Introduction, Measuring planar (2D) and spatial (3D) motions
2. Sensors
3. Fourier transforms
4. Discrete time signals and systems
5. Z transforms
6. Filtering
7. Simple tools for system identification for buildings
8. Nonparametric (Spectral) methods for system identification
9. Parametric methods for system identification
10. Hands-on practice with instrumentation and data collection
11. Hands-on practice with system identification using real data

Course References:
1. *L. Ljung*, System Identification: Theory for the User, 1999.
2. *MathWorks*, System Identification Toolbox User Manual, 2013.
3. *J. S. Bendat and A. G. Piersol*, Random Data: Analysis and Measurement Procedures, 1993.
4. *J. S. Bendat and A. G. Piersol*, Engineering Applications of Correlation and Spectral Analysis, 1993.
5. *J. A. Cadzow*, Discrete-Time Systems: An Introduction with Interdisciplinary Applications, 1973.
6. *M. H. Hayes*, Digital Signal Processing (Schaum's Outlines), 1999.
7. *F. Scherbaum*, Of Poles and Zeros, 2001.

Course Title: Structural Health Monitoring

University/Institute: Columbia University

Instructor: Raimondo Betti

Course Description: This course will serve as an introduction to Structural Health Monitoring, with particular emphasis on system identification methods. Students will learn different ways of modelling dynamical systems and some of the most advanced identification methods. Emphasis will be given to civil engineering applications.

Syllabus:
1. Introduction: What is Structural Health Monitoring; definition of damage; brief overview of sensors; model-based and data-based methods.
2. Model Description: SDOF systems in time and frequency domain; state space formulation; Laplace transform; Z-transform; Discrete Time Fourier Transform; Discrete Fourier Transform; MDOF systems; integration schemes; auto-regressive models.
3. Numerical Methods for SHM: Least squares; eigenvalue decomposition; singular value decomposition; pseudo-inverse; QR decomposition; Principal Component Analysis.
4. Auto-Regressive Model Identification: ARX models; estimation and prediction errors; model order selection; Akaike and Bayesian information criteria; Markov Parameters from ARX models; state space representations from ARX models.
5. Identification in the Frequency Domain: Fundamentals of modal identification; Frequency Response Function; peak picking; Frequency Domain Decomposition (FDD).
6. System Identification using Kalman Filter: Minimal Realization Theory; Eigensystem Realization Algorithm (ERA, ERA/DC); Observer Kalman filter Identification (OKID), both in its input-output and output-only formulations; Deterministic Intersection and Deterministic Projection.
7. Stochastic Subspace Identification: Overview; identification of deterministic systems and stochastic systems; Multivariate Linear Regression (MLR); Canonical Correlation Analysis (CCA); Principal Component Analysis (PCA); Enhanced Canonical Correlation Analysis (ECCA).
8. Identification of Mass-Damping-Stiffness Models: From state space models to MCK models; effect of incomplete instrumentation – reduced order models; from reduced order to full order models – matrix expansion; non-uniqueness issues.
9. Damage Detection: Use of statistical pattern recognition; review of probability; damage sensitive features; Mahalanobis Square Distance; hypothesis testing; likelihood ratio; outlier analysis.

Suggested Reading:
1. *Doebling, Farrar, Prime and Shevitz*, Damage identification and health monitoring of structural and mechanical systems from changes in their vibrations charateristics: A literature review, Los Alamos National Lab, Report: LA-13070-MS, 1996.
2. *Carden and Fanning*, Vibration based condition monitoring: A review, Structural Health Monitoring, Vol. 3, pp. 355–377, 2004.
3. *P. Van Overschee and B. De Moor*, Subspace Identification for Linear Systems, Kluwer Academic Publishing.
4. *C. R. Farrar and K. Worden*, Structural Health Monitoring –A Machine Learning Perspective, Wiley.
   Lists of reading materials also provided at the end of each topic.

Course Title: Vibration-Based Structural Health Monitoring

University/Institute: IIT Kanpur

Instructor: Suparno Mukhopadhyay and Samit Ray Chaudhuri

Course Description: The course presents some commonly used vibration-based modal identification techniques, in the context of structural health monitoring. The course begins with introducing the SHM problem along with different associated issues. Different ways to model dynamic systems, and relationships between such models are then discussed. This is followed by methods to identify such dynamic models. Both time and frequency domain system identification techniques, in the input-output and output-only scenarios are presented. The problem of optimal instrument locations is also briefly discussed. The course includes a field application of modal identification of a campus building using ambient vibration data.

Syllabus:

1. Introduction: Motivation; SHM vs. NDE; Levels of damage detection; Damage sensitive features; Steps involved in SHM – Operational evaluation, Data acquisition and processing, Feature extraction/identification, Decision making; Environmental and operational variability; Sensors – types, pros/cons.
2. Fundamentals of vibration analysis: SDOF and MDOF systems, Impulse response, Fourier and Laplace transform, Transfer function, FRF, Eigenvalues and eigenvectors, Complex eigenvalue problem and complex modes, Classical and non-classical damping.
3. State space representation: Continuous time models, Complex modes from state space model, Transfer function from state space model, Continuous time to discrete time models, Markov parameters, Z-transfer functions and ARX models from discrete time state space models.
4. Basics of random vibrations and signal processing.
5. Eigensystem Realization Algorithm: Markov parameters from Input-Output Data, State space models from Markov parameters, Minimal realization, Free vibration case, Natural Excitation Technique, Stabilization diagram.
6. Observer Kalman Filter Identification: Input-Output and Output Only variants.
7. Auto-regressive models: Modeling, identification, model selection.
8. Peak Picking, Frequency domain decomposition.
9. Mode shape normalization and expansion, added mass experiments, SEREP.
10. Optimal input and sensor locations.
11. Field experiment using piezoelectric accelerometers and force balanced accelerometers.

Suggested Reading:

1. *J. -N. Juang,* Applied System Identification, Prentice Hall.
2. *J.-N. Juang, M. Q. Phan*, Identification and Control of Mechanical Systems, Cambridge University Press.
3. *D. J. Ewins*, Modal Testing: Theory, Practice and Application, Wiley.
4. *C. R. Farrar, K. Worden*, Structural Health Monitoring – A Machine Learning Perspective, Wiley.
5. http://faculty.uml.edu/pavitabile/22.515/ME22515_PDF_downloads.htm
6. *F. N. Catbas, T. Kijewski-Correa, A. E. Aktan*, Structural Identification of Constructed Facilities, ASCE SEI Committee Report.

Course Title: Structural Health Monitoring Principles

University/Institute: University of California, San Diego

Instructor: Charles R. Farrar

Course Description: A modern paradigm of structural health monitoring as it applies to structural and mechanical systems will be presented. Concepts in data acquisition, feature extraction, data normalization, and statistical modeling will be introduced in an integrated context. Students will understand: (a) a four-part statistical pattern recognition paradigm for developing structural health monitoring system solutions; (b) the application and integration of signal processing, structural dynamics, statistics and machine learning to each part of the structural health monitoring paradigm; and (c) the challenges associated with developing a structural health monitoring system for *in situ* aerospace, civil and mechanical infrastructure applications.

Syllabus:

1. Define structural health monitoring (SHM), provide a brief history of SHM development, review traditional nondestructive evaluation techniques (NDE) and distinguish SHM from NDE, introduce the four-part statistical pattern recognition paradigm for SHM, discuss operational evaluation.
2. Review signal processing and basic statistics necessary for SHM.
3. Overview of sensing, data acquisition and telemetry technologies that have been used for SHM.
4. Introduction to guided wave approaches to damage detection.
5. Introduce the concept of damage-sensitive features (DSFs). Discuss features based on waveform or image comparison and features based upon parameters of models fit to measured data. Discussion of DSFs focusing on cases where damage causes a system to exhibit nonlinear response characteristics.
6. Discuss the influence of operational and environmental variability on the damage detection process. Show examples of errors that can result when such variability is not addressed. Provide strategies for dealing with these sources of variability based on regression modeling, data acquisition system design and machine learning.
7. Motivate the need for statistical classification algorithms from "real-world" test case. Discussion of various statistical classification algorithms focusing on unsupervised learning methods (clustering and outlier detection). Introduce *k*-means clustering, hierarchical clustering, control charts.
8. Discussion of different classification algorithms with emphasis on supervised learning approaches (group classification and regression). Introduce classifiers based on machine learning (K-nearest neighbor, discriminant analysis, support vector machine, neural network, Gaussian process models).
9. Define fundamental axioms for structural health monitoring. Discuss current outstanding research issues and challenges for transitioning SHM research to practice.

   Experimental data sets provided for different homework problems: signal processing; applying statistical algorithms; analyzing guided wave data; extraction of DSFs based on nonlinear response characteristics; development of "look-up table" for data normalization. Other homework problems include: using modal parameters as DSFs, damage detection through model-updating; construction of control charts for damage detection using unsupervised learning; building SVM linear classifier.

Course References:

1. *C. R. Farrar, K. Worden*, Structural Health Monitoring – A Machine Learning Perspective, Wiley.
2. MATLAB – Signal Processing Toolbox, Statistics and Machine Learning Toolbox.

Course Title: Instrumentation and Signal Processing

University/Institute: Virginia Tech

Instructor: Rodrigo Sarlo

Course Overview: The primary course objectives are 1) to understand how to design experiments and instrumentation for static and dynamic testing and 2) how to interpret physical data using a variety of signal processing tools. The course will cover the basic operational principles and implementation of various sensing modalities, including strain, vibration, and vision. Digital signal processing concepts such as sampling, filtering, noise, and correlation are covered in detail, both in the time and frequency domains. Applications in Structural Health Monitoring of civil infrastructure and other topics of interest are discussed. Advanced concepts, such as wavelet transforms and modal analysis are introduced.

Syllabus:

1. Introduction to data acquisition and measurement concepts
    - Components of a data acquisition system
    - Discrete time signals
2. Statistics and uncertainty review
    - Independence, discrete and continuous random variables
    - Two random variables, joint, marginal, and conditional distributions
    - Design of experiments and types of uncertainty
    - T-tests, Z-tests, goodness of fit tests
3. Time domain analysis
    - Covariance, cross-correlation
    - Time domain filtering (i.e. moving average)
4. Frequency domain analysis
    - Introduction to complex analysis
    - Nyquist theorem
    - Fourier transform and Discrete Fourier Transform
    - Power Spectral Density
5. Sensors, operational principles and modeling
    - Strain
    - Vibration
    - Pressure
    - Sonar and ultrasound
    - Vision
6. Advanced Concepts
    - Wavelet transforms,
    - Modal analysis
    - Digital Image Correlation
    - Stereo-vision, egomotion

Course References:

1. *R. S. Figliola, D. E. Beasley*, Theory and Design for Mechanical Measurements, 6th Ed., Hoboken, NJ : Wiley & Sons, 2011.
2. *J. Fraden*, Handbook of Modern Sensors, 4th Ed., New York, NY: Springer, 2010.

Course Title: System Identification

University/Institute: Rice University

Instructor: Satish Nagarajaiah

Course Description: Introduction to modelling and system identification of dynamic systems and structures to wind, wave and earthquake forces. MATLAB programming and use of computer software.

Syllabus:

1. Introduction to Linear Systems.
2. Continuous and Discrete State Space Models and Methods
3. Linear System Response – Time and Frequency Domain
4. Observers, State Estimation
5. Markov Parameters, ARX Models
6. Pseudo-Inverse, SVD, Low-rank Approximation
7. Regression, Least Squares, Regularization, Model Selection and Validation
8. Probability-Random Variables and Processes-Statistical Properties
9. Correlation Methods and Spectral Analysis
10. ACF – CCF – Power Spectra
11. Non-Parametric (Transfer Function Estimate) and Parametric Methods
12. Modal Identification, Stabilization Diagram
13. Linear Time-Invariant Systems
    a. ERA, OKID
    b. SSI
    c. FDD, Peak Picking
    d. Kalman Filter (KF)
14. Brief Introduction to Advanced Topics in Linear and Nonlinear System Identification
    a. Time-Frequency Methods
    b. Blind Source Separation
    c. Sparse Structural System Identification
    d. Model Selection and Validation

Project: USC Hospital Building – System Identification from Northridge Earthquake data

Course References:

1. *J. -N. Juang,* Applied System Identification, Prentice Hall.
2. *L. Ljung*, System Identification: Theory for the User, Prentice Hall.

Course Title: Structural Monitoring

University/Institute: Stanford University

Instructor: Hae Young Noh

Course Overview: This course will introduce monitoring systems for civil structures and human occupants. Such monitoring systems enable us to understand the performance of the physical structures and humans and help us diagnose/prognose their critical status by combining our structural engineering knowledge with emerging technologies, such as sensor network, IoT, and data analytics. The ultimate goals of these monitoring systems are to ensure the safety and functionality of the monitored physical systems and understand the status of the occupants to improve their quality of life. Examples include but are not limited to structural health monitoring in both post-disaster and everyday scenarios, occupancy estimation, indoor environment monitoring, occupant activity monitoring, etc.

The course will include lectures that provide theoretical background on structural data acquisition and analysis using both physics- and data-based approaches for various systems, with an emphasis on the underlying physical interpretations and their practical usage through examples and applications. Students will use knowledge from structural engineering, mechanics, statistics, machine learning, artificial intelligence, and data management. The topics include linear time-invariant systems, time-series modeling, frequency analysis, filtering, feature extraction, and various machine learning techniques in the context of structural systems and human occupants.

One key aspect of the course is for students to understand the overall process from obtaining structural data to specific application performance in a systematic way to achieve application goals. To this end, students will be required to do course projects, where they can have hands-on experience on integrating and implementing what they have learned from lectures.

Syllabus:

1. Structural data acquisition
    - Transducers and data acquisition system
    - Signal conditioning
2. Structural system modeling
    - Linear time-invariant system, convolution
    - Excitation input modeling, power spectral density
    - Frequency domain analysis
3. Feature extraction
    - Physics-based feature extraction
    - Data-driven feature extraction
4. Information learning
    - Machine learning and statistical modeling
    - Hypothesis test and error analysis
    - Classification

Course References:

1. *C. R. Farrar, K. Worden*, “Structural Health Monitoring – A Machine Learning Perspective,” Wiley 2012.
2. *T. Hastie, R. Tibshirani, and J. Friedman*, “The Elements of Statistical Learning,” Springer 2009.

Course Title: Principles and Applications of Sensors for Engineering

University/Institute: University of Massachusetts Lowell

Instructor: Alessandro Sabato

Course Overview: The course focuses on defining concepts and operational principles of various sensing technologies and their applications for condition monitoring of aerospace, civil, and mechanical engineering systems and materials. Analytical and experimental background of commonly used transducers, their data acquisition protocols, and signal processing techniques in time and frequency domains are discussed. A strong emphasis is provided on non-contact and optical techniques, including mono/stereo computer vision and thermal infrared for nondestructive evaluation and subsurface inspection. The concepts discussed in the lectures are analyzed in depth and applied through practical projects, demonstrations, and hands-on experiments on laboratory-scale structures.

Syllabus:

1. Introduction to sensors, data acquisition systems, and basic signal processing
    - Analog and digital signals
    - Time/Frequency conversion (i.e., DFT, FFT, Transfer function, FRF)
    - Digital filters and filter characterization
    - Averaging, Correlation, Cross-correlation, coherence, spectral density
2. Accelerometers and modal measurements
    - Operational principles of and types of accelerometers
    - Experimental and operational modal analysis
    - Mode shapes and operating deflection shapes
3. Infrared imaging
    - Operational principles of micro-bolometers
    - Types of infrared thermography (i.e., active, passive, pulse, etc.)
    - Principal component thermography (PCT)
    - Notable applications (e.g., sub-surface damage detection, heat loss assessment)
4. Computer vision
    - Principles of image processing, camera calibration, and camera motion compensation
    - Digital image correlation and three-dimensional digital image correlation
    - Stereophotogrammetry and drone-borne computer vision
    - Motion magnification
5. Acoustic emission and ultrasonic transducers
    - Principles of operation
    - Notable applications

Each lecture will have a recitation component followed by a laboratory part in which students will perform hands-on experiments using the discussed sensors/techniques. The goal of the laboratory is to collect data that will be used to complete the project associated with the topic of the lecture.

Course References:

1. *McClellan, J. H., Schafer, R. W., and Yoder, M. A.*, "DSP First (2nd Edition)", Pearson, 2015.
2. MECH 5195 - Princ. And App. Of Sensors for Eng. – UML Syllabus Spring 2023 (link)

Course Title: Structural Health Monitoring

University/Institute: Shantou University

Instructor: Li Dongsheng

Course Description: This course will explain basic theories of structural health monitoring, especially in damage identification and modal analysis, covering the applications of these theories in civil engineering. Advanced methods will also be introduced such as techniques for separating EOC(changing Environment and Operational Conditions) effects from structural damage, nonlinear effects and its influence in SHM, machine learning and AI-based methods etc.

Syllabus:

1. Introduction: The basic concepts, development trends, necessity of Structural Health Monitoring (SHM), and the main challenges faced by SHM.
2. Common Methods in Structural Health Monitoring: Least Squares Method; Eigenvalue Decomposition; Singular Value Decomposition; Pseudoinverse; QR Decomposition; Laplace Transform; Z-transform; Discrete-Time Fourier Transform; Discrete Fourier Transform.
3. Basic methods of damage identification: frequency-based damage identification methods, mode shape-based damage identification methods, flexibility matrix-based damage identification methods.
4. Sensitivity Analysis: Sensitivity Analysis of Eigenvalues, Eigenvectors, and Frequency Response Functions (FRF), including Fox Method, Quasi-static Method, Wang B.P. Method, and Nelson Method.
5. Theories of Optimal Sensor Placement: Modal Kinetic Energy Method, Drive Point Residue Method, Effective Independence Method, Space domain sampling Method, Information Entropy, and Bayesian Penalty Function. And Evaluation Criteria for Optimal Sensor Placement is also introduced.
6. Modal Analysis: Frequency Domain Modal Analysis Methods, such as Least Square Frequency Domain Method and Time Domain Modal Analysis Methods such as Least Square Complex Exponential (LSCE) Method. Moreover, concepts of Operational Modal Analysis, Peak Picking Method, Two Measurement Methods of Frequency Response Function, Stochastic Subspace Identification (SSI) Method, and Stabilization Diagram are briefly introduced.
7. Model Updating: Static and Dynamic Condensation Methods, Lagrange Multiplier Method and Penalty Function Method, Cross Model Cross Mode Method, Minimum Variance Method, etc.; Model Validation and Nonlinear Model Updating.
8. Separating EOC(changing Environment and Operational Conditions) effects from structural damage: Linear Regression, Bilinear Model, Polynomial Regression Model, Cointegration, Principal Component Analysis, Factor Analysis, Mahalanobis Distance, Kalman Filter etc.
9. Machine Learning: Linear Regression, Neural Networks, Multilayer Feedforward Networks, Convolutional Neural Networks, Transfer Learning, and Physics Integrated Neural Networks (PINN).

Course References:

1. *Charles R. Farrar and K. Worden*, Structural Health Monitoring - A Machine Learning Perspective, Wiley, 2013.
2. *Ewins, D. J.* Modal Testing: Theory, Practice and Application, Wiley, 2009.
3. *Friswell M. I., Mottershead J. E.*, Finite Element Model Updating in Structural Dynamics, Springer Dordrecht, 1995.