



Optimization-Based Modeling and Design of Electronic Circuits (Graduate Course)

Jan-May 2019
19-22 hrs Wednesdays
Classroom W-113/114

Instructor Information

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General Description

This course will enable students to apply advanced numerical optimization techniques to modeling and design of electronic circuits. Students will gain basic skills on fundamental classical optimization methods, as well as on some state-of-the-art engineering optimization techniques. Students will implement some of these techniques and apply them to electronic circuits for design optimization, parameter extraction, and surrogate modeling. Applications to low and high-frequency electronic circuits will be considered, including electromagnetics-based modeling and design. The use of numerical software and commercially available electronic circuit CAD tools for hands-on experience will be emphasized throughout the course.

Prerequisites

Students taking this course should have already accredited the graduate course on Simulation Methods for Electronic Circuits.

Objectives

By the end of the course, the student will be able to:

- A. Manipulate the essential techniques of matrix algebra and multidimensional calculus for numerical optimization (APPLICATION)
- B. Identify the fundamental notation and terminology used in mathematical optimization (COMPREHENSION)
- C. Analyze some of the most important methods for unconstrained optimization (ANALYSIS)
- D. Implement practical techniques to formulate and solve constrained optimization problems (SYNTHESIS)
- E. Analyze some of the most important methods for solving multidimensional systems of nonlinear equations (ANALYSIS)
- F. Implement in Matlab basic optimization algorithms as well as basic algorithms for solving



nonlinear systems (SYNTHESIS)

- G. Formulate and solve electronic circuit design problems as optimization problems (SYNTHESIS)
- H. Formulate and solve electronic circuit modeling problems as optimization problems (SYNTHESIS)
- I. Identify the basic principles and applications of space mapping in circuit modeling and design (COMPREHENSION)
- J. Implement an space mapping optimization algorithm to solve synthetic design problems (SYNTHESIS)
- K. Identify the general characteristics of surrogate modeling and develop a basic functional modeling approach applied to electronic circuits (SYNTHESIS)
- L. Identify the applications of neural networks for electronic circuit modeling and design (COMPREHENSION)
- M. Formulate and implement the problem of training artificial neural networks as an optimization problem (SYNTHESIS)
- N. Make scientific comparisons between different optimization methods as applied to electronic circuits modeling and design (EVALUATION)
- O. Efficiently exploit commercially available simulation tools for circuit modeling and design (APPLICATION)

General Contents

- 1. A review on matrix computations
 - 1.1. Basic matrix operations, singular matrices, norms, quadratic forms
 - 1.2. Gradient, directional derivative, Jacobian, Hessian
 - 1.3. Multidimensional Taylor series expansions
 - 1.4. Multidimensional geometry (neighborhood, line segments, intervals, hyperplanes, etc.)
 - 1.5. Convex sets, convex and nonconvex functions
- 2. Introduction to numerical optimization
 - 2.1. Unconstrained optimization (terminology)
 - 2.2. Types of minimizers
 - 2.3. Examples of objective functions
 - 2.4. Constrained optimization (mathematical formulations)
 - 2.5. Linear and non-linear programming
 - 2.6. Identifying minimizers
 - 2.7. Stopping criteria
 - 2.8. Line search methods
 - 2.9. Steepest descent direction
 - 2.10. Trust region methods
- 3. Unidimensional search methods
 - 3.1. Unidimensional optimization problems
 - 3.2. Well-behaved and badly-behaved functions
 - 3.3. Multimodal and unimodal functions
 - 3.4. Methods for optimizing unimodal functions
 - 3.5. Golden section method



- 3.6. Fibonacci method
- 3.7. Quadratic interpolation method
- 3.8. Available commands in Matlab for unidimensional problems
4. Unconstrained multidimensional methods
 - 4.1. Generic line search method
 - 4.2. Conjugate gradient methods
 - 4.3. Global and local convergence
 - 4.4. Rate of convergence
 - 4.5. Newton's methods
 - 4.6. Damped Newton method
 - 4.7. Quasi-Newton methods
 - 4.8. Multi-dimensional search methods
5. Constrained multidimensional methods
 - 5.1. Constrained optimization problem
 - 5.2. Box constraints
 - 5.3. Methods for constrained optimization problems
 - 5.4. Elimination of variables
 - 5.5. Penalty methods
 - 5.6. Sequential quadratic programming (SQP)
 - 5.7. Minimax formulations
6. Systems of nonlinear equations (SNLEq)
 - 6.1. Solving SNLEq vs unconstrained optimization problems
 - 6.2. Linear models from Taylor series expansions
 - 6.3. Newton method
 - 6.4. Broyden method
 - 6.5. Stopping criteria for solving SNLEq
7. Circuit design using classical optimization methods
 - 7.1. Nominal circuit design optimization
 - 7.2. Pre-assigned parameters, design parameters and optimization variables
 - 7.3. Independent variables and optimizable responses
 - 7.4. A general formulation to circuit design optimization
 - 7.5. Objective functions
 - 7.6. Minimax optimization to circuit design
 - 7.7. Constrained formulation to design optimization
 - 7.8. Examples using different objective function formulations
8. Circuit parameter extraction using classical optimization methods
 - 8.1. Nominal parameter extraction
 - 8.2. Basic definitions
 - 8.3. Non-linear least squares formulation to parameter extraction (PE)
 - 8.4. General p -th norm formulations to PE
 - 8.5. Examples of PE for equivalent circuit models
 - 8.6. Local minima in parameter extraction (PE)
 - 8.7. Statistical parameter extraction
9. Space mapping techniques
 - 9.1. Space mapping origins and terminology
 - 9.2. The general aim of space mapping
 - 9.3. Designing with a fine and a coarse model
 - 9.4. Input space mapping approach to design



- 9.5. The space mapped solution versus the optimal solution
- 9.6. An algorithm for Broyden-based input SM
- 9.7. An algorithm for constrained Broyden-based input SM
- 9.8. Examples
- 10. An introduction to surrogate modeling
 - 10.1. Linear regression
 - 10.2. Response surface approximations
 - 10.3. Modeling by polynomial functional surrogates
- 11. Modeling and design of electronic circuits using artificial neural networks (ANN)
 - 11.1. Biological neural networks
 - 11.2. Definitions of artificial neural networks (ANN)
 - 11.3. Linear neurons
 - 11.4. Inner product nonlinear neurons
 - 11.5. Euclidean distance nonlinear neurons
 - 11.6. Typical activation functions
 - 11.7. Multilayer perceptrons
 - 11.8. Radial basis functions
 - 11.9. Recurrent neural networks
 - 11.10. Pre-processing training data
 - 11.11. ANN training methods
 - 11.12. Conventional ANN-based modeling and optimization
 - 11.13. Neural EM-design exploiting knowledge
- 12. Neural space mapping methods for modeling and design
 - 12.1. SM-based neuromodeling
 - 12.2. Neural space mapping optimization
 - 12.3. Inverse space mapping: linear and neural
 - 12.4. Examples

Relationship between Contents and Objectives

	1	2	3	4	5	6	7	8	9	10	11	12
A	✓	✓	✓	✓	✓	✓						
B	✓	✓										
C		✓	✓	✓								
D					✓							
E						✓						
F		✓	✓	✓	✓	✓						
G							✓			✓		
H								✓	✓			
I									✓			✓
J									✓			✓
K										✓	✓	✓
L											✓	✓
M											✓	✓
N			✓	✓		✓	✓	✓	✓	✓		
O							✓	✓	✓	✓	✓	



Course Skeleton

For the proposed course skeleton it is assumed: a group of up to 18 students; 3 hours per week of class meetings during approximately 16 weeks; simulation software available at ITESO or at home (for SPICE simulation: WinSpice, OrCad PSpice, Electronic Workbench, or any other similar circuit simulator; for EM simulation: Sonnet, Momentum, EM-Pro, COMSOL, HFSS, or CST Microwave Studio; for high-frequency circuit simulation: ADS, APLAC, Qucs, or NI-AWR; for general computing: Matlab, SciLab, or Octave).

It is also expected that the student will be able to dedicate an average of 8 hours of work per week to this course, including attending classes.

Week	Activity	Week	Activity
1	Contents 1	9	Contents 7
2	Contents 1-2	10	Contents 8
3	Contents 2	11	Contents 9
4	Contents 3	12	Contents 9-10
5	Contents 4	13	Contents 10-11
6	Contents 4	14	Contents 11-12
7	Contents 5	15	Final project
8	Contents 6	16	Final project

Assessment

The overall grade in this course will be built from the following elements:

Assignments	65%
Project	30%
Participation	5%

Each student will realize a final project during the course. The topic chosen must be approved by the instructor. The final project report must be submitted following a template that will be indicated in the course. Students will make a technical presentation on their final project selected. Depending on the selected topic and class size, the project and the corresponding presentation can be realized individually or in teams of up to 2 students. The presentation will be evaluated not only by the instructor but also by the classmates. Further instructions about the final project report and corresponding technical presentation will be delivered later on.

Quality of students' participation during the lectures will be graded. This participation will be evaluated based on student's attitude and performance during class: punctuality, willingness to ask relevant questions, respect to others, attention during class, ability to answer questions, etc.

Teaching Methods

This course uses a variety of teaching methods including: lecturing, seminars, computer simulations, assignments, readings, project report writing and self-conducted research work.

Important information related to the course will be posted in the instructor's web site throughout the semester. Open and frequent communication with the instructor is encouraged. Collaboration between the students is also encouraged.



The course will be conducted in Spanish. Most of the written material for the course will be available in English.

References

Instructor's web site
http://desi.iteso.mx/erayas/cir_opt.htm

Books

- E. K. P. Chong and S. H. Zak, *An Introduction to Optimization*. New York, NY: Wiley-Interscience, 1996.
- P. E. Frandsen, K. Jonasson, H. B. Nielsen and O. Tingleff, *Unconstrained Optimization*. Lyngby, Denmark: Department of Mathematical Modeling, Technical University of Denmark, 1999.
- P. Venkataraman, *Applied Optimization with MATLAB Programming*. New York, NY: Wiley-Interscience, 2002.
- A. Ravindran, K. M. Ragsdell and G. V. Reklaitis, *Engineering Optimization: Methods and Applications*. Hoboken, NJ: Wiley, 2006.
- S. Koziel and L. Leifsson, *Surrogate-Based Modeling and Optimization: Applications in Engineering*, New York, NY: Springer, 2013.
- S. Koziel, X-S Yang, and Q. J. Zhang, *Simulation-Driven Design Optimization and Modeling for Microwave Engineering*, London, England: Imperial College Press, 2013.
- D. Budimir, *Generalized Filter Design by Computer Optimization*, Norwood, MA: Artech House, 1998.
- V. Litovski and M. Zwolinski, *VLSI Circuit Simulation and Optimization*, Great Britain: Chapman and Hall, 1997.
- S. Haykin, *Neural Networks: A Comprehensive Foundation*. New Jersey, MA: Prentice Hall, 1999.
- Q. J. Zhang and K. C. Gupta, *Neural Networks for RF and Microwave Design*. Norwood, MA: Artech House, 2000.
- D. G. Swanson and W. J. R. Hofer, *Microwave Circuit Modeling Using Electromagnetic Field Simulation*. Norwood, MA: Artech, 2003
- H. Kogure, Y. Kogure, and J. C. Rautio, *Introduction to RF Design Using EM Simulators*. Tokyo, Japan: Artech House, 2010
- R. W. Pryor, *Multiphysics Modeling Using COMSOL 4: A First Principles Approach*. Dulles, VA: Mercury Learning and Information, 2012.

Other References

Some references on direct optimization:



J. E. Rayas-Sánchez, “Optimal design of a shunt-series feedback amplifier: a tutorial introduction to circuit optimization,” Internal Report *CAECAS-06-03-R*, Jul. 2006.

J. E. Rayas-Sánchez, “An improved EM-based design procedure for single-layer substrate integrated waveguide interconnects with microstrip transitions,” in *IEEE MTT-S Int. Microwave Workshop Series in Region 9 (IMWS2009-R9) on Signal Integrity and High-Speed Interconnects*, Guadalajara, Mexico, Feb. 2009, pp. 27-30.

J. E. Rayas-Sánchez and E. Estrada-Arámbula, “EM-based design optimization of microstrip lines traversing a rectangular gap in the reference plane,” in *Int. Conf. on Synthesis, Modeling, Analysis and Simulation Methods and Applications to Circuit Design (SMACD)*, Seville, Spain, Sep. 2012, pp. 197-200.

D. Becerra-Pérez and J. E. Rayas-Sánchez, “Optimization of the stub-alternated and serpentine microstrip structures to minimize far-end crosstalk,” in *IEEE Conf. Electrical Performance of Electronic Packaging and Systems (EPEPS 2012)*, Tempe, AZ, Oct. 2012, pp. 109-112.

A. Viveros-Wacher, R. Baca-Baylón, F. E. Rangel-Patiño, M. A. Dávalos-Santana, E. A. Vega-Ochoa, and J. E. Rayas-Sánchez, “Jitter tolerance acceleration using the golden section optimization technique,” in *IEEE Latin American Symp. Circuits and Systems Dig. (LASCAS 2018)*, Puerto Vallarta, Mexico, Feb. 2018, pp. 1-4.

Some references on space mapping:

J. W. Bandler, R. M. Biernacki, S. H. Chen, P. A. Grobelny, and R. H. Hemmers, “Space mapping technique for electromagnetic optimization,” *IEEE Trans. Microwave Theory Tech.*, vol. 42, no. 12, pp. 2536–2544, Dec. 1994.

J. W. Bandler, “Have you ever wondered about the engineer's mysterious ‘feel’ for a problem?,” *IEEE Canadian Rev.*, no. 70, pp. 50-60, 2013, Summer.

J. W. Bandler, Q. Cheng, S.A. Dakroury, A.S. Mohamed, M.H. Bakr, K. Madsen and J. Søndergaard, “Space mapping: the state of the art,” *IEEE Trans. Microwave Theory Tech.*, vol. 52, pp. 337-361, Jan. 2004.

D. Echeverría-Ciaurri, *Multi-Level Optimization: Space Mapping and Manifold Mapping*, Ph.D. Thesis, Department of Informatics, University of Amsterdam, Amsterdam, Holand, 2007.

S. Koziel, Q. S. Cheng, and J. W. Bandler, “*Space mapping*,” *IEEE Microwave Magazine*, vol. 9, pp. 105-122, Dec. 2008.

J. E. Rayas-Sánchez, “Power in simplicity with ASM: tracing the aggressive space mapping algorithm over two decades of development and engineering applications,” *IEEE Microwave Magazine*, vol. 17, no. 4, pp. 64-76, Apr. 2016.

J. E. Rayas-Sánchez, F. Lara-Rojo and E. Martínez-Guerrero, “A linear inverse space mapping (LISM) algorithm to design linear and nonlinear RF and microwave circuits,” *IEEE Trans. Microwave Theory Tech.*, vol. 53, pp. 960-968, Mar. 2005.

J. E. Rayas-Sánchez and V. Gutiérrez-Ayala, “EM-based Monte Carlo analysis and yield prediction of microwave circuits using linear-input neural-output space mapping,” *IEEE Trans. Microwave Theory Tech.*, vol. 54, pp. 4528-4537, Dec. 2006.

Q. S. Cheng, J. W. Bandler and J. E. Rayas-Sánchez, “Tuning-aided implicit space mapping,” *Int.*



J. RF and Microwave CAE, vol. 18, pp. 445-453, Sep. 2008.

J. E. Rayas-Sánchez and N. Vargas-Chávez, "A linear regression inverse space mapping algorithm for EM-based design optimization of microwave circuits," in *IEEE MTT-S Int. Microwave Symp. Dig.*, Baltimore, MD, Jun. 2011, pp. 1-4.

J. C. Cervantes-González, C. A. López, J. E. Rayas-Sánchez, Z. Brito-Brito and G. Hernández-Sosa, "Return-loss minimization of package interconnects through input space mapping using FEM-based models," in *Proc. SBMO/IEEE MTT-S Int. Microwave Optoelectronics Conf. (IMOC-2013)*, Rio de Janeiro, Brazil, Aug. 2013, pp. 1-4.

J. C. Cervantes-González, J. E. Rayas-Sánchez, C. A. López, J. R. Camacho-Pérez, Z. Brito-Brito, and J. L. Chavez-Hurtado, "Space mapping optimization of handset antennas considering EM effects of mobile phone components and human body," *Int. J. RF and Microwave CAE*, vol. 26, no. 2, pp. 121-128, Feb. 2016.

F. Leal-Romo, M. Cabrera-Gómez, J. E. Rayas-Sánchez, and D. M. García-Mora, "Design optimization of a planar spiral inductor using space mapping," in *Int. Conf. Electrical Performance of Electronic Packaging and Systems (EPEPS 2017)*, San Jose, CA, Oct. 2017, pp. 1-3.

F. E. Rangel-Patiño, J. E. Rayas-Sánchez, A. Viveros-Wacher, E. A. Vega-Ochoa, and N. Hakim, "High-speed links receiver optimization in post-silicon validation exploiting Broyden-based input space mapping," in *IEEE MTT-S Int. Conf. Num. EM Mutiphysics Modeling Opt. (NEMO-2018)*, Reykjavik, Iceland, Aug. 2018, pp. 1-3.

Some references on ANN-based methods:

A. Viveros-Wacher and J. E. Rayas-Sánchez, "Analog fault identification in RF circuits using artificial neural networks and constrained parameter extraction," in *IEEE MTT-S Int. Conf. Num. EM Mutiphysics Modeling Opt. (NEMO-2018)*, Reykjavik, Iceland, Aug. 2018, pp. 1-3.

F. E. Rangel-Patiño, J. E. Rayas-Sánchez, A. Viveros-Wacher, J. L. Chávez-Hurtado, E. A. Vega-Ochoa, and N. Hakim, "Post-silicon receiver equalization metamodeling by artificial neural networks," *IEEE Trans. Computer-Aided Design of Integrated Circuits and Systems*, vol. *, no. **, pp. **, *** 2018 (early access).

J. E. Rayas-Sánchez, *Neural Space Mapping Methods for Modeling and Design of Microwave Circuits*, Ph.D. Thesis, Dept. of Electrical and Comp. Eng., McMaster University, Hamilton, Canada, 2001.

J. E. Rayas-Sánchez, "EM-based optimization of microwave circuits using artificial neural networks: the state of the art," *IEEE Trans. Microwave Theory Tech.*, vol. 52, pp. 420-435, Jan. 2004.

J. W. Bandler, M. A. Ismail, J. E. Rayas-Sánchez and Q. J. Zhang, "Neuromodeling of microwave circuits exploiting space mapping technology," *IEEE Trans. Microwave Theory Tech.*, vol. 47, pp. 2417-2427, Dec. 1999.

M. H. Bakr, J. W. Bandler, M. A. Ismail, J. E. Rayas-Sánchez and Q.J. Zhang, "Neural space mapping optimization for EM-based design," *IEEE Trans. Microwave Theory Tech.*, vol. 48, pp. 2307-2315, Dec. 2000.

J. W. Bandler, J. E. Rayas-Sánchez and Q. J. Zhang, "Yield-driven electromagnetic optimization via space mapping-based neuromodels," *Int. J. RF and Microwave CAE*, vol. 12, pp. 79-89, Jan. 2002.



J. W. Bandler, M. A. Ismail, J. E. Rayas-Sánchez and Q. J. Zhang, "Neural inverse space mapping for EM-based microwave design," *Int. J. RF and Microwave CAE*, vol. 13, pp. 136-147, March 2003.

V. Gutiérrez-Ayala and J. E. Rayas-Sánchez, "Neural input space mapping optimization based on nonlinear two-layer perceptrons with optimized nonlinearity," *Int. J. RF and Microwave CAE*, vol. 20, pp. 512-526, Sep. 2010.

J. E. Rayas-Sánchez and Q. J. Zhang, "On knowledge-based neural networks and neuro-space mapping," in *IEEE MTT-S Int. Microwave Symp. Dig.*, Montreal, Canada, Jun. 2012, pp. 1-3.

Some references on surrogate modeling:

M. B. Yelten, T. Zhu, S. Koziel, P. D. Franzon, and M. B. Steer, "Demystifying surrogate modeling for circuits and systems," *IEEE Circuits and Systems Magazine*, vol. 12, pp. 45-63, First Quarter 2012.

J. E. Rayas-Sánchez, J. Aguilar-Torrentera and J. A. Jasso-Urzúa, "Surrogate modeling of microwave circuits using polynomial functional interpolants," in *IEEE MTT-S Int. Microwave Symp. Dig.*, Anaheim, CA, May 2010, pp. 197-200.

J. E. Rayas-Sánchez and N. Vargas-Chávez, "Design optimization of microstrip lines with via fences through surrogate modeling based on polynomial functional interpolants," in *IEEE Conf. Electrical Performance of Electronic Packaging and Systems (EPEPS 2010)*, Austin, TX, Oct. 2010, pp. 125-128.

J. L. Chavez-Hurtado and J. E. Rayas-Sánchez, "Polynomial-based surrogate modeling of RF and microwave circuits in frequency domain exploiting the multinomial theorem," *IEEE Trans. Microwave Theory Techn.*, vol. 64, no. 12, pp. 4371-4381, Dec. 2016.

Software Tools

Introduction to Matlab, Yossi Farjoun, MIT
<http://ocw.mit.edu/ans7870/resources/farjoun/index.html>

Matlab
<https://www.mathworks.com/products/matlab.html>

Octave
<http://www.gnu.org/software/octave/>

SciLab
<http://www.scilab.org/>

WinSpice circuit simulator
<http://www.winspice.com/>

Cadence (Pspice Orcad)
<http://www.orcad.com/resources/orcad-downloads>

APLAC (NI AWR) high-frequency circuit simulator



<http://www.awrcorp.com/products/innovative-technologies/aplac>

NI AWR Design Environment
<http://www.awrcorp.com/products>

Qucs, high frequency circuit simulator
<http://qucs.sourceforge.net/>

Keysight ADS and EM-Pro
<http://www.keysight.com/en/pc-1297113/advanced-design-system-ads?nid=-34346.0&cc=MX&lc=eng>

Sonnet, EM simulator
<http://www.sonnetsoftware.com/>

COMSOL Multiphysics
<http://www.comsol.com/>

CST Microwave Studio
<http://www.cst.com/>

Other Websites

CAECAS Research Group at ITESO
<http://www.desi.iteso.mx/caecas/>

Servicio de Aplicaciones Remotas del ITESO:
<https://aplicaciones.iteso.mx>

Technical University of Denmark, Department of Informatics and Mathematical Modeling:
Prof. Kaj Madsen, https://www.researchgate.net/profile/Kaj_Madsen
Prof. Hans Bruun Nielsen, https://www.researchgate.net/profile/Hans_Nielsen6

NOTA: En caso de alguna dificultad o confusión respecto de este programa de estudios (por estar en idioma inglés), favor de consultar directamente con el profesor.