

Module 01

Course Syllabus, Prerequisites, Applications, Course Overview

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EE 5243: Optimization and Control of Cyber-Physical Systems

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Course Instructor: Background & Interests

Background

- Born and raised in Beirut, Lebanon
- Finished my Ph.D. in ECE from Purdue University in August 2015
- Undergraduate education: American University of Beirut — Class of 2011, B.E., ECE
- Assistant Professor, ECE Department @ UTSA
- At UTSA since . . . August, 2015

My Ultimate Objective

Understand how complex systems operate and utilize this knowledge to create tools & control algorithms that would be leveraged to solve system-level challenges

Essentially, this should improve the quality of our lives...Hopefully!

Module 01 Outline

- 1 You will tell me about yourselves: careers, objectives, education
- 2 Course syllabus and expectations (*very high ones, believe me!*)
- 3 Course outline
- 4 The fun stuff starts — we will introduce CPSs and chat about them

Part I — Your Turn to Introduce Yourself! 😊

Part II — Course Syllabus, Outline, and HW # 1

Course Webpage & Communication

Course Pages:

- For lecture notes, homework postings, uploads, projects, and readings please visit the course webpage on UTSA Blackboard:
<http://utsa.blackboard.com>
- For video lecture recordings, please visit this Dropbox link and download the videos to watch them offline <https://bit.ly/35GQafc>.
- You will need to download the VLC paper on Mac/Windows to view the videos offline. The Dropbox video player cuts the videos so you shouldn't view the videos using that player.
- I will be uploading the videos for the week at the beginning of it.

Office Hours:

- Tuesdays, Thursdays, 9:00 – 10:30
- Office hours will be virtual through Zoom:
<https://utsa.zoom.us/j/97557156027>
- Or by appointment

Course Description

- Modeling, analysis and design of cyber-physical systems (CPS)
- Who should/can take the course?
- Ask yourself if you are genuinely interested in CPSs in general...
- ...And control and optimization of CPSs, in specific

Course Description — Cont'd

- Fundamentals of CPSs are covered with emphasis on the control and the optimization aspects
- Covered topics: networked control systems, linear systems theory and design, state-estimators
- Applications in smart-grids and water networks are discussed throughout the course but mostly towards the end if time permits

Main References

- No textbook is required for the class
- Lecture notes will be provided as handouts or presentation slides
- You may need to consult the following, mostly, free texts:
 - C. T. Chen, *Linear System Theory and Design*, Oxford University Press, 1995.
 - F. Y. Wang and D. Liu, *Networked Control Systems, Theory and Applications*, Springer-Verlag London, 2008.
 - S. Boyd, L. El Ghaoui, E. Feron and V. Balakrishnan, *Linear Matrix Inequalities in System and Control Theory*, SIAM, 1994. Book webpage: <http://web.stanford.edu/~boyd/lmibook/>.
 - S. Boyd and L. Vandenberghe, *Convex Optimization*, Cambridge University Press, 2004. YouTube videos for the class: <https://www.youtube.com/watch?v=McLq1hEq3UY> and book webpage: <http://web.stanford.edu/~boyd/cvxbook/>.
- Research papers

Course Objectives & Expected Outcomes

- This course is designed for graduate students who are interested in learning about CPSs
- Course includes a wide range of topics related to CPSs
- At the end of the semester, students are expected to have a good understanding of the basic principles governing CPSs' operation...
- ...And a reasonable depth related to a specific CPS topic that relates to their projects

Prerequisites

An undergraduate-level understanding of:

- Multi-variable calculus
- Control theory and feedback systems
- Linear algebra
- Basic optimization principles
- Basics related to the aforementioned topics will be covered in the first two weeks of classes
- Most importantly: the will to learn

Grading Policy

- Homework (25%)
- One exam (25%)
- Project (50%) — divided as follows: initial proposal (20%), progress report (20%), final report (60%)

Course Grade Cutoffs

- A-, A, A+: 85–100
- B-, B, B+: 70–84
- C-, C, C+: 55–69
- D-, D, D+: 40–54
- F: ≤ 39

Important Dates

Project Proposal	February 10th, 23:59:59
Progress Report	March 27th, 23:59:59
Exam	April 20, time TBA
Final Report	May 10, 23:59:59

Programming Tools

- MATLAB will be required for homework assignments and course projects
- Students can obtain the discounted student version of MATLAB

Class Policies

- Course projects
- Emailing me
- Aim of the project (and reward)
- Late submission policy
- Changes to the syllabus

Tentative Class Schedule

Part I — CPS Review & Background	≈ 5–6 classes
█ Course introduction & syllabus, prerequisites, major applications, course overview	
Part II — Linear & Nonlinear Networked Systems Theory	≈ 4–5 classes
█ Recent relevant theories on linear and nonlinear systems	
Part III — State Observation & Estimation of CPSs	≈ 4–5 classes
█ Dynamic state estimation of dynamic CPSs	
Part IV — CPSs & Convex Optimization	≈ 3–4 classes
█ Basic principles on convex optimization for generic systems	
Part V — Progress Reports Presentations	≈ 1–2 classes
█ Students will give short presentations on their progress reports	
Part VI — Optimal Control of CPSs	≈ 1–2 classes
█ Linear quadratic regulator, optimal state-feedback control, principle of optimality	
Part VII — Exam	1 class
█ In class exam	
Part VIII — Networked Control Systems	≈ 1–2 classes
█ Recent results on networked control systems, fault detection, cyber-attacks	
Part IX — Applications	≈ 1–2 classes
█ Smart-grids, transportation networks, robotics	
Part X — Project Presentations	≈ 2–3 classes
█ Students will present their projects	

Part III — Cyber-Physical Systems: History and Introduction

Cyber-Physical Systems — The *Ubiquity is Real!*

- CPSs: integrating computing, data analysis, communication, & control with physical processes
- Infrastructures are reliant on CPS-techs & communication networks
 - *The Physics and The Cyber: Intertwined responsibilities*



- CPSs are *inherently uncertain*; *vulnerable* to hackers & natural adversities

Trust Issues

Can we trust computers to manage, control, and optimize physics?

CPS History [Jeschke, 2013]

1898: Nikola Tesla's Radio-Controlled Boat — *Teleautomaton*

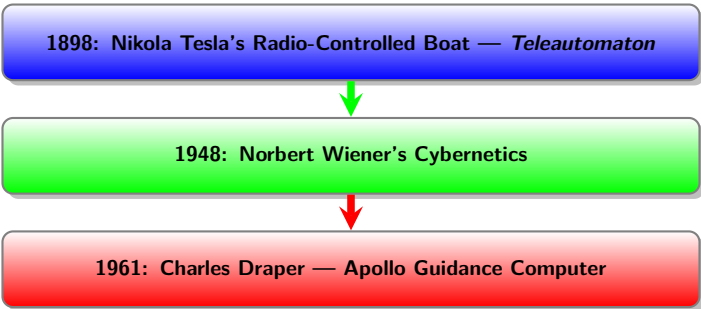
CPS History [Jeschke, 2013]

1898: Nikola Tesla's Radio-Controlled Boat — *Teleautomaton*

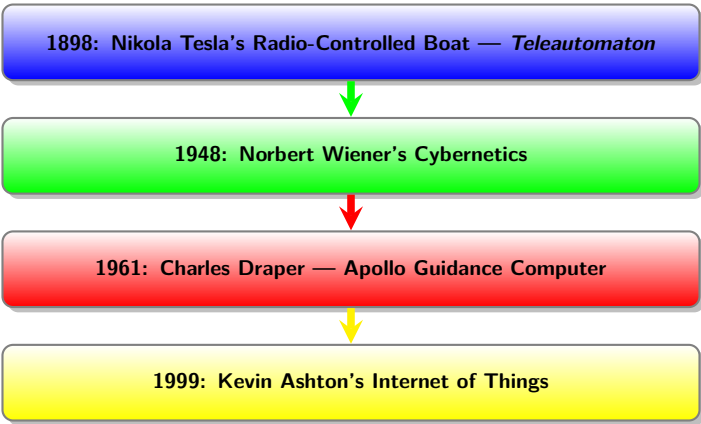


1948: Norbert Wiener's Cybernetics

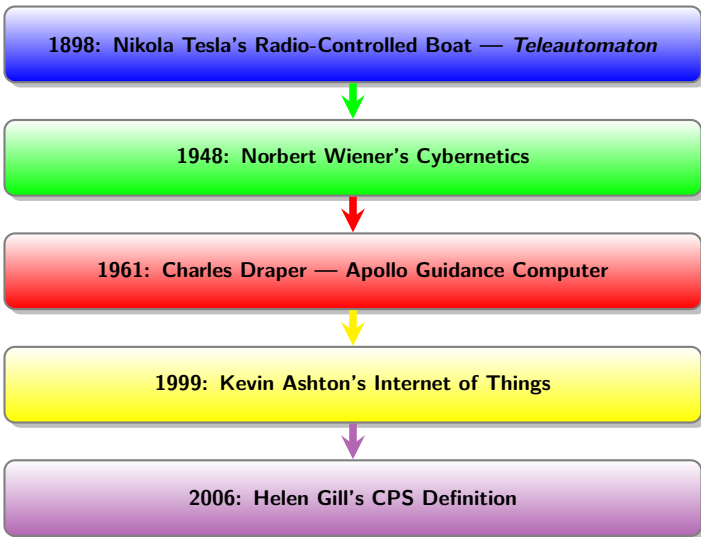
CPS History [Jeschke, 2013]



CPS History [Jeschke, 2013]



CPS History [Jeschke, 2013]



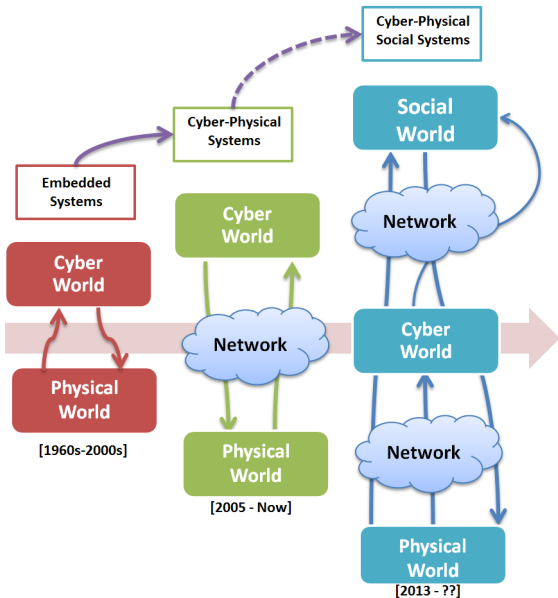
Helen Gill's CPS Definition

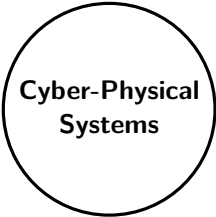
“A CYBER-PHYSICAL SYSTEM (CPS) IS AN INTEGRATION OF COMPUTATION WITH PHYSICAL PROCESSES. EMBEDDED COMPUTERS AND NETWORKS MONITOR AND CONTROL THE PHYSICAL PROCESSES, USUALLY WITH FEEDBACK LOOPS WHERE PHYSICAL PROCESSES AFFECT COMPUTATIONS AND VICE VERSA.

AS AN INTELLECTUAL CHALLENGE, CPS IS ABOUT THE INTERSECTION, NOT THE UNION, OF THE PHYSICAL AND THE CYBER. IT IS NOT SUFFICIENT TO SEPARATELY UNDERSTAND THE PHYSICAL COMPONENTS AND THE COMPUTATIONAL COMPONENTS.

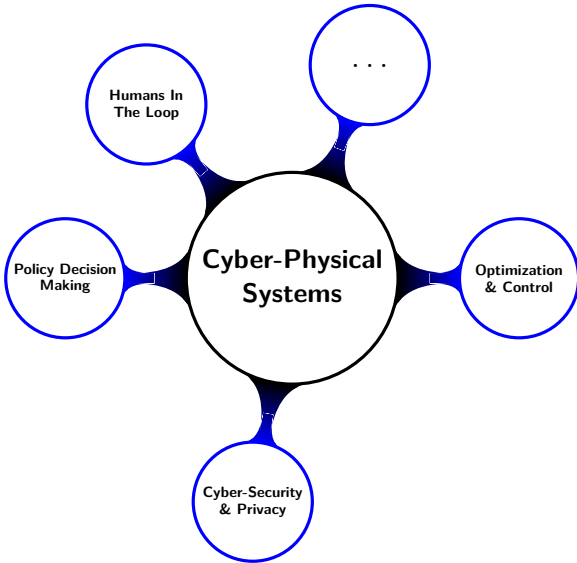
WE MUST INSTEAD UNDERSTAND THEIR INTERACTION. THE DESIGN OF SUCH SYSTEMS, THEREFORE, REQUIRES UNDERSTANDING THE JOINT DYNAMICS OF COMPUTERS, SOFTWARE, NETWORKS, AND PHYSICAL PROCESSES. IT IS THIS STUDY OF JOINT DYNAMICS THAT SETS THIS DISCIPLINE APART.” — HELEN GILL, NSF, 2006

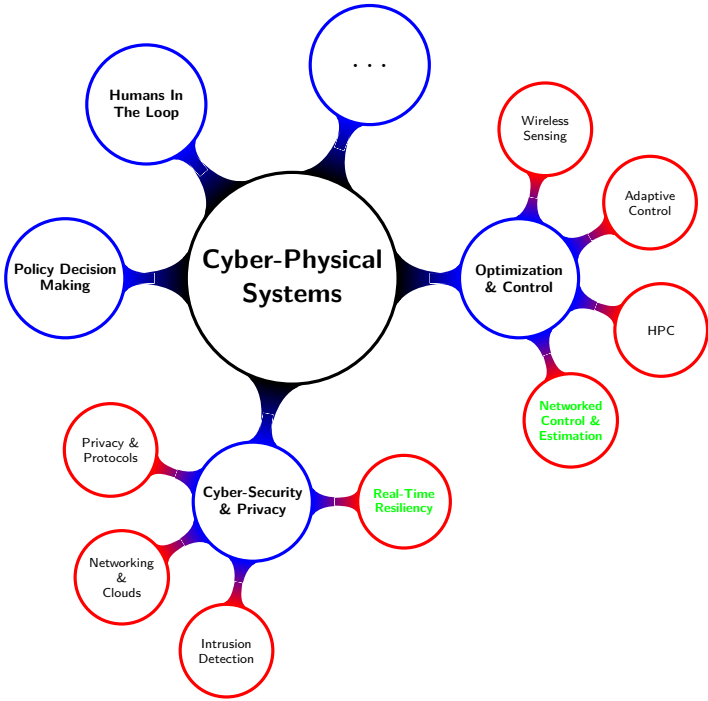
CPS & CPSS Evolution

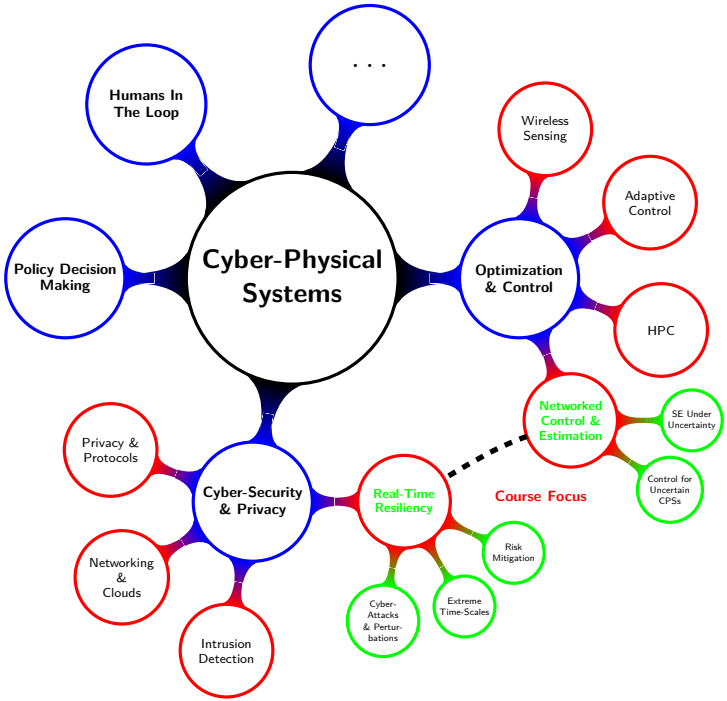




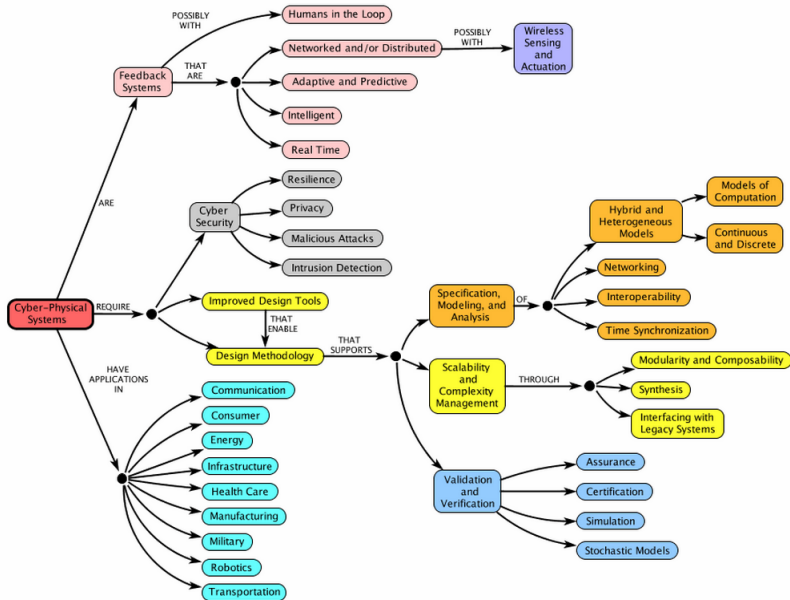
**Cyber-Physical
Systems**







Another Concept Map [Lee et al., 2014]



CPS Vision & Mission

- **Vision:** *building secure & resilient critical infrastructure*
- **Mission:** *leading efforts to secure infrastructure by **managing risk & enhancing resilience** through open collaborations* — a DHS mission [DHS, 2015]

Research Focus

Developing secure computational methods for uncertain CPSs with applications to dominant CPS applications

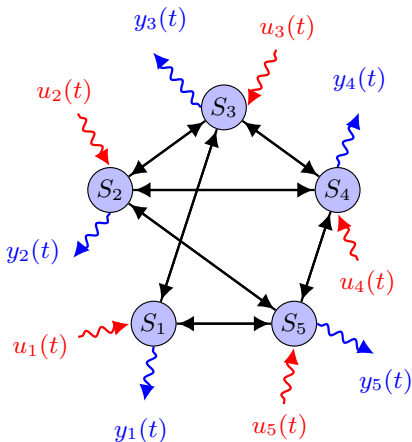
CPSs — A Dynamical Model Representation

In this class, we consider a general class of nonlinear, interconnected nodes of a CPS which can be modeled as:

$$\dot{\mathbf{x}}(t) = \mathbf{A}\mathbf{x}(t) + \mathbf{B}_u\mathbf{u}(t) + \mathbf{B}_w\mathbf{w}(t) + \phi(\mathbf{x}) \quad (1)$$

$$\mathbf{y}(t) = \mathbf{C}\mathbf{x}(t) + \mathbf{D}_u\mathbf{u}(t) + \mathbf{D}_v\mathbf{v}(t). \quad (2)$$

- This model assumes a lot of things...
- Nodes are connected via a network (graph)
- Assume that there are N nodes in the network
- The global state \mathbf{x} consists of each nodal agent's states $\mathbf{x}_i \in \mathbb{R}^{n_{x_i}}$, $i = 1, \dots, N$, hence $\mathbf{x} = [\mathbf{x}_1^\top, \dots, \mathbf{x}_N^\top]^\top$.
- Each node has a set of **inputs** $\mathbf{u}_i \in \mathbb{R}^{n_{u_i}}$ and **measurements** $\mathbf{y}_i \in \mathbb{R}^{n_{y_i}}$
- The mapping from the input to state vector can thus be written in the form $\mathbf{B}_u\mathbf{u} = \text{blkdiag}(\mathbf{B}_{u_1}, \dots, \mathbf{B}_{u_N})[\mathbf{u}_1^\top, \dots, \mathbf{u}_N^\top]^\top$
- Mapping from state to measurement:
 $\mathbf{C}\mathbf{x} = \text{blkdiag}(\mathbf{C}_1, \dots, \mathbf{C}_N)[\mathbf{x}_1^\top, \dots, \mathbf{x}_N^\top]^\top$
- System nonlinearity can be expressed in terms of the nodal agent nonlinearities as $\phi(\mathbf{x}) = [\phi_1^\top(\mathbf{x}_1), \dots, \phi_N^\top(\mathbf{x}_N)]^\top$



S_i : subsystem i defined by

$$\dot{x}_i = f(x_i, x_j, u_i, w_i), y_i = g(x_i, u_i, v_i)$$

$u_i(t)$: control input; $y_i(t)$: output

$w_i(t), v_i(t)$: unknown inputs and disturbances

Examples in Water, Transportation, and Power Systems

- Dynamics of water hydraulics in drinking water distribution networks: Section II of <https://arxiv.org/pdf/2003.01837.pdf>
- Dynamics of water quality in drinking water distribution networks: Sections II and II in <https://arxiv.org/pdf/2009.01298.pdf>
- Dynamics of traffic on transportation systems and highways: Section III of <https://arxiv.org/pdf/1812.02128.pdf>
- Dynamics of multi-machine power networks with renewables: Section II of <https://arxiv.org/pdf/1802.09071.pdf>

References I

DHS (2015). <http://www.dhs.gov/office-infrastructure-protection>.

Gallup (2005). <http://www.gallup.com/poll/17881/electricity-retains-power-greatest-invention.aspx>.

Jeschke, S. (2013). Cyber-physical systems — history, present and future.

URL http://www.ima-zlw-ifu.rwth-aachen.de/fileadmin/user_upload/INSTITUTSCLUSTER/Publikation_Medien/Vortraege/download//CPS_27Feb2013.pdf

Lee, E. A., Asare, P., Broman, D., Torngren, M., & Sunder, S. S. (2014). <http://cyberphysicalsystems.org/>.

Sridhar, S., Hahn, A., & Govindarasu, M. (2012). Cyber-physical system security for the electric power grid. *Proceedings of the IEEE*, 100(1), 210–224.

Questions And Suggestions?



Thank You!

Please visit

engineering.utsa.edu/ataha

IFF you want to know more 😊