AOE 5984: Cyber-Physical Systems and Distributed Control

Course Syllabus

**Instructor:** Dr. Kyriakos G. Vamvoudakis

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**Time & Location:** TR 3:30 PM to 4:45 PM

318 Randolph Hall

**Office Hours:** 11:00 AM - 12:30 PM Tuesdays & Thursdays or by appointment

**Course Web Page:** http://www.dept.aoe.vt.edu/~kyriakos/ and https://canvas.vt.edu/

**Required Texts:** There is no required text. The instructor will provide notes and research papers.

**Prerequisites:** Undergraduate linear algebra, probability and signal processing, understanding of modern (state space) control theory

**Required Software:** Student Edition of Matlab

**Course Description and Topics:** In this course, we will review several recent advancements in cyber-physical systems and distributed control. Topics will include core principles of CPS, differential equations to model physical processes, graph theory and CPS communication structures, examples with single and double integrator dynamics, time varying structures and matrix analysis of graphs, control loops in CPS, cooperative optimal control, cooperative adaptive control, game theoretic frameworks for secure cooperative control, control and estimation over lossy and attacked networks, intrusion and fault detection in CPS, differential and temporal logic for safety of execution, machine learning in CPS.

**Course Topics:**

I. Introductory Topics

A. Introduce the core principles behind CPS
B. Differential Equations as Models of Physical Processes
C. The Concept of Synchronization in Complex Systems
D. Known Networks

II. Graph Theory and CPS Communication Structure

A. Graph Theory
B. Eigen structure of Graph Laplacian Matrix
C. Single Integrator Dynamics and Average Consensus

D. Leader and Leaderless Cases
E. Motion Invariants for First-Order Consensus
F. Comparison of Discrete and Continuous Time Systems
G. Double Integrator Dynamics
H. Bipartite Consensus
I. Time Varying Graphs
J. Matrix Analysis of Graphs
K. Advanced Topics and Research Papers

III. Control Loops and Importance of Control and Actuation in CPS
A. Lyapunov Techniques for Control
B. Potential Fields and Motion Control
C. Pinning Control

IV. Cooperative Optimal Control
A. Stability and Optimality
B. Performance Selection
C. Constraints on Graph Topology
D. Advanced Topics and Research Papers

V. Cooperative Adaptive Control
A. Synchronization
B. Adaptive Tuning Laws
C. Stability
D. Advanced Topics and Research Papers

VI. Secure Cooperative Control
A. Game Theoretic Frameworks
B. Research Papers and Advanced Topics

VII. Control and Estimation over Lossy and Attacked Networks
A. Introduction
B. Basics of Hybrid and Impulsive Systems
C. Hybrid Games
D. Advanced Topics and Research Papers

VIII. Intrusion Detection and Fault Detection in Cyber-Physical Systems
A. Introduction
B. Advanced Topics and Research Papers

IX. Differential and Temporal Logic
A. Introduction on Safety of Execution of CPS
B. Advanced Topics and Research Papers

X. Topics on Machine Learning and CPS
A. Advanced Topics and Research Papers

**Tentative Grading Policy**
Tentative Grading: Homework and Paper Presentations 25%-Midterm Project 35%-Final Project 40%
**Student Learning Outcomes:**

1. Understand distributed control and shared resources in cyber-physical systems.

   **Assessment**- homework design projects.

2. Understand the basic different types of graphs that dictate the flow of information.

   **Assessment**- homework design projects and examinations.

3. Ability to perform designs with various tools using MATLAB.

**Assessment**- design and simulation projects assigned in homework.

4. Understand cooperation and control over adversarial and "lossy" networks.

**Assessment**- design and simulation projects in homework.

5. Understand intrusion detection and identification.

**Assessment**- design and simulation projects in homework, exams.

6. Learn to perform a literature search and prepare a research paper with a unified presentation and exposition on a selected topic.

**Assessment**- Final Project Report.

**Homework Assignments:**

- Due at the beginning of the class on the due date. Solutions to the homework will be posted on the web at the time that they are due. Therefore NO LATE HOMEWORK will be accepted.
- Electronic submissions will be accepted before the class starts.
- Late homework will not be accepted without formal documentation of extenuating circumstances (e.g. a note from a Dean, a physician, etc.).

**Course Policies:** 1. NO CELL PHONES are allowed during lecture. 2. Be on time to class. Tardy is discouraged. 3. No make-up exams/quizzes. If you miss the exam, a zero score will be assigned to the missed exam/quiz. 4. If you miss a class due to personal emergency or medical reasons, please be sure to inform the instructor by e-mail. 5. Homework assignments are to be submitted by the due date. You may discuss homework problems with your classmates, but you are responsible for your own works. 6. After an assignment grade has been posted online, students must see the instructor within one week if they wish to discuss the assignment and their work.

**Principles of Community:** Students are expected to be polite and professional when interacting with one another and with the instructor. Abusive or insensitive behavior will not be tolerated. Virginia Tech's Principles of Community govern student conduct: http://www.diversity.vt.edu/principles-of-community/principles.html

**Honor System:** Graduates of Virginia Tech's engineering program have very high standards of personal and professional integrity. It is the responsibility of Virginia Tech's students and faculty to ensure that this legacy continues. The Undergraduate Honor Code pledge that each member of the university community agrees to abide by states:

> "As a Hokie, I will conduct myself with honor and integrity at all times. I will not lie, cheat, or steal, nor will I accept the actions of those who do."

Students enrolled in this course are responsible for abiding by the Honor Code. A student who has doubts about how the Honor Code applies to any assignment is responsible for obtaining specific guidance from the course instructor before submitting the assignment for evaluation. Ignorance of the rules does not exclude any member

of the University community from the requirements and expectations of the Honor Code. For additional information visit: https://www.honorsystem.vt.edu/

**Academic Support:** The instructor will provide assistance through normal protocols, such as office hours, but cannot serve as a private tutor. Virginia Tech has numerous resources to support student achievement. For information about academic support services, please see: http://www.undergraduate.vt.edu/Subpages/aca-supp_index_SCMS.html

**Special Accommodations:** Special accommodations can be made for students with disabilities. Please bring any such issues to the instructor's attention *no later than the second week of class*. For information on the types of accommodations that are available see http://www.ssd.vt.edu/

**Emergency Preparedness:** The Office of Emergency Preparedness has developed the following flyer outlining simple steps to follow when preparing for or responding to an emergency: http://www.emergency.vt.edu/help/resources-help/studentPreparedness.pdf

| Tentative Roadmap | | | Spring 2017 (AOE 5984) | |
|---|---|---|---|---|
| Number of Lecture | date | day | Topic | Reading Assignments |
| 1 | 17-Jan | tue | Introduction to CPS | - |
| 2 | 19-Jan | thurs | Differential Equations as Models of Physical Processes (Physical Part) | - |
| 3 | 24-Jan | tue | Graph Theory and Communication Structure in CPS (Cyber Part) | - |
| 4 | 26-Jan | thurs | Graph Theory and Communication Structure in CPS (Cyber Part) | - |
| 5 | 31-Jan | tue | Graph Theory and Communication Structure in CPS (Cyber Part) | Provided Research Papers |
| 6 | 2-Feb | thurs | Graph Theory and Communication Structure in CPS (Cyber Part) | Provided Research Papers |
| 7 | 7-Feb | tue | Control Loops and Importance of Control and Actuation in CPS | - |
| 8 | 9-Feb | thurs | Control Loops and Importance of Control and Actuation in CPS | Provided Research Papers |
| 9 | 14-Feb | tue | Control Loops and Importance of Control and Actuation in CPS | Provided Research Papers |
| 10 | 16-Feb | thurs | Cooperative Optimal Control | - |
| 11 | 21-Feb | tue | Cooperative Optimal Control | Provided Research Papers |
| 12 | 23-Feb | thurs | Cooperative Adaptive Control | - |
| 13 | 28-Feb | tue | Cooperative Adaptive Control | Provided Research Papers |
| 14 | 2-Mar | thurs | Secure Cooperative Control | Provided Research Papers |
| 15 | 7-Mar | tue | No Lecture/Spring Break | - |
| 16 | 9-Mar | thurs | No Lecture/Spring Break | - |
| 17 | 14-Mar | tue | Secure Cooperative Control | Provided Research Papers |
| 18 | 16-Mar | thurs | Control and Estimation over Lossy and Attacked Networks | Provided Research Papers |
| 19 | 21-Mar | tue | Control and Estimation over Lossy and Attacked Networks | Provided Research Papers |
| 20 | 23-Mar | thurs | Intrustion Detection and Fault Detection in CPS | Provided Research Papers |
| 21 | 28-Mar | tue | Intrustion Detection and Fault Detection in CPS | Provided Research Papers |
| 22 | 30-Mar | thurs | Differential and Temporal Logic for Safety of Execution of CPS | Provided Research Papers |
| 23 | 4-Apr | tue | Differential and Temporal Logic for Safety of Execution of CPS | Provided Research Papers |
| 24 | 6-Apr | thurs | Differential and Temporal Logic for Safety of Execution of CPS | Provided Research Papers |
| 25 | 11-Apr | tue | Topics on Machine Learning and CPS | Provided Research Papers |
| 26 | 13-Apr | thurs | Topics on Machine Learning and CPS | Provided Research Papers |
| 27 | 18-Apr | tue | Topics on Machine Learning and CPS | Provided Research Papers |
| 28 | 20-Apr | thurs | Topics on Machine Learning and CPS | Provided Research Papers |
| 29 | 25-Apr | tue | Advanced Topics | Provided Research Papers |
| 30 | 27-Apr | thurs | Advanced Topics (Projects are Due) | - |
| 31 | 2-May | tue | Project Presentations | - |

**These descriptions and timelines are subject to change at the discretion of the Instructor.**