Multi-agent Robotic Systems (Special Topic)

(SYSE 6v80.002 / EECS 7v90.002 / MECH 6v29.002)

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<tr><td>Lecture Schedule</td><td>Tue. & Thu.
8:30 am – 9:45 am</td><td>Semester</td><td>Fall 2022</td></tr>
<tr><td>Lecture Room</td><td>ECSN 2.120</td><td>Pre-requisite</td><td>• Control systems (undergraduate level),
• Linear algebra (undergraduate level),
• Linear systems (graduate / preferrable),
• The course will be mostly self-contained.

(Feel free to contact the instructor if you are unsure of the needed background)</td></tr>
<tr><td>Instructor</td><td>Waseem Abbas</td><td>Contact</td><td>waseem.abbas@utdallas.edu</td></tr>
<tr><td>Office</td><td>ECSN 3.720</td><td>Office Hours</td><td>TBD.</td></tr>
<tr><td>Course Description</td><td colspan="3">This course will provide a detailed overview of the distributed decision architecture of the cooperative and distributed control for multirobot and multiagent systems. The goal is to understand, and design distributed controllers and strategies that rely on local interactions between network agents (robots) to achieve global objectives. We will demonstrate and analyze the control-theoretic properties of multirobot systems and the influence of the underlying network topology on the dynamical behavior of these networked systems. These distributed control strategies and analysis will then be applied for solving various problems, including formation control, coverage control, connectivity and topology control, resilient and fault-tolerant control, and self-organization in multirobot systems.

(Link to some introductory slides: https://docs.google.com/presentation/d/1BUcnAjUBlHcCH3SUW1c8p86oIyzMOuwz/edit?usp=sharing&ouid=107662415827888275123&rtpof=true&sd=true)</td></tr>
<tr><td>Course Overview</td><td colspan="3">A networked control system consists of a set of dynamical units, such as robots, that interact over an information exchange network for its coordinated operation and behavior. The bigger objective is to characterize and design control strategies for a collection of these decision-making components with possibly limited processing capabilities, locally sensed information, and limited communications, all seeking to achieve a collective objective. Further examples of such a setting include mobile sensor networks, transportation and autonomous vehicle systems, multi-robot systems, social networks, and biological networks. We will see how local cooperation between individuals can lead to complex global behaviors.

This course will provide an overview of the tools and techniques that have proven instrumental for studying multirobot and networked multiagent systems as well as outline potential research directions.

The course has following major components:</td></tr>
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Network Models and Properties (graphs, random graphs, proximity networks, time-varying and state-dependent networks, combinatorial and algebraic properties, robustness, and resilience in networks)

Dynamics over Networks (Decentralized control, consensus dynamics and its extensions, stability and convergence analysis, leader-based control, network controllability, distributed estimation, adversarial interactions, and resilient consensus).

Applications in Multirobot and Sensor Networks (consensus-based algorithms, formation control, coverage control, Voronoi-based cooperation strategies, connectivity maintenance, topology control, self-organization, distributed optimization).

A deep understanding of the interplay between the network topology, often abstracted as a graph structure, and the dynamics of the network components lies at the core of design and analysis of these networked systems. We seek answers to the following interesting questions:

- In distributed networks, how can we achieve complex global behaviors from the local interactions of nodes (components, devices, agents) with limited capabilities?
- How are the network dynamics and the underlying network topology interrelated and affect each other?
- How can we apply our understanding of the relationship between network dynamics and underlying network structure to understand networking behaviors in various natural systems as well as design engineered systems with desired attributes?
- How can we design distributed, scalable, and resilient algorithms that can achieve desired global objective through local interactions?

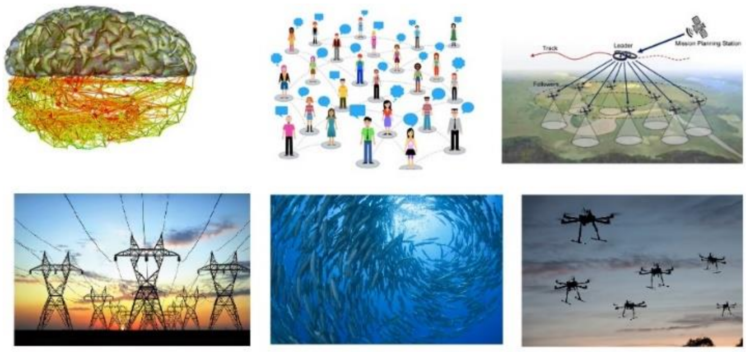

Figure: Networks are everywhere.

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Expected Outcomes

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Upon completion of this course, students will be able to:

1. Recognize and analyze the distributed decision architecture of the cooperative control in multirobot systems.
2. Design distributed controllers and strategies that rely on local interactions between network components to achieve global objectives.
3. Demonstrate and analyze control theoretic properties of network control systems by the algebraic and combinatorial structure of the underlying network topologies.

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	4. Apply distributed control strategies for solving various problems such as formation control and coverage control in multirobot systems. 5. Identify and evaluate research directions in networked, multiagent and cooperative control.
Textbooks	**Textbook:** • *Graph-Theoretic Methods in Multiagent Networks*, by M. Mesbahi and M. Egerstedt, Princeton University Press, 2010. • I will provide *notes* and *relevant reference papers*. *Optional:* • *Robot Ecology*, by M. Egerstedt, Princeton University Press, 2022 • *Distributed Control of Robotic Networks*, by F. Bullo, J. Cortes, and S. Martinez, Princeton 2009.
Grading Policy	• Assignments 25% • Midterm 25% • Group Activities 5% • Project/Research 15% • Final 30% There will be about five assignments. • The purpose of the research project is to think innovatively and apply the learned tools and techniques to solve the relevant problems. A brief report (paper) is expected at the end of the project. Further details regarding the project will be shared later.
Assignments	Homework assignments must be submitted as per instructions and timelines provided and will be discussed in class as time permits. The emphasis will be placed on *effort* and *completeness*, not just correctness. You are allowed to discuss problems on the assignment; however, everyone must write their own solution. The focus should be on the learning of the material. An assignment that is not reasonably neat and readable will be marked down. Late assignments will **not** be accepted. Solutions to assignments will be provided after the deadline.
Group Activities	Students will be divided into groups of 2-3 students. Each group is expected to meet approximately once a month and work on the specific tasks assigned. The main purpose is to provide students opportunities to discuss topics in a group setting and help each other. We expect three group meetings during the semester. Further details will be provided later.
Exams	Exams will be closed book and closed notes. No calculators or electronic communication devices are allowed. Exams will be held during the class time. Please note that there will **not** be any make-up exams, so mark down the exam dates in your calendars.
Honor Code	Although you are encouraged to work together to learn the course material, the assignments and exams must be completed individually. All conduct in this

	course will be governed by the University of Dallas honor code (https://policy.utdallas.edu/utdsp5003).
Class Participation	You are strongly encouraged to attend every class; lectures will substantially augment the material presented in the text, and all quizzes/exams are administered during regular lectures.
Requirements Related to Public Health Measures	UT Dallas will follow the public health and safety guidelines put forth by the Centers for Disease Control and Prevention (CDC), the Texas Department of State Health Services (DSHS), and local public health agencies that are in effect at that time during the Fall 2022 semester to the extent allowed by state governance.
Academic Support Resources	The information contained in the following link lists the University's academic support resources for all students. Please see http://go.utdallas.edu/academic-support-resources.

Topics*

Introduction Multiagent systems and cooperative control Distributed decision architecture and its applications Swarming phenomena Rendezvous/Consensus problem – A canonical problem
Network Models and Graphs Introduction to graphs Proximity graphs as network models Matrices associated with graphs Graph spectra Connectivity in graphs
The Agreement Protocol – Static and Dynamic Cases Reaching decentralized agreements Distributed consensus – static case Linear systems – A review Disagreement vectors Stability analysis and convergence Distributed consensus – dynamic case Switched networks – hybrid Systems Lyapunov based stability Edge-tension functions Leader-follower networks Example: Distributed estimation Biological Models: Flocking and swarming Alignment and Kuramoto's coupled oscillators
Leader Based Control Leader-follower networks Network controllability (graph-based control) Upper bounds: Equitable partitions for network controllability Lower bounds: Graph distances and network controllability,

zero forcing sets and network controllability Network feedback Applications
Resilience in Multiagent and Multirobot Systems Adversarial interactions and their models Resilient consensus protocol Scalar case Multi-dimensional case Resilient network topologies – necessary and sufficient conditions Resilient consensus in sparse networks
Connectivity Control Potential function-based connectivity control in multiagent systems
Formation Control Formations in multiagent and multirobot systems Formation graphs Rigidity and persistence Distance based formation control
Coverage Control Coverage control for multirobot systems Gabriel graphs and triangulations Voronoi tessellations Lloyds algorithm Graph grammars – A tool for 'building' networks
Network Formations Graph grammars and self configuration in networks Erdos-Renyi model, Scale-free network model, Preferential attachment model
Potential Topics Distributed learning and optimization in multirobot systems Resource allocation problems in networks Consensus over random graphs
Project / Research
Review & Research Frontiers

<u>Important note:</u>

* It is a tentative schedule. There might be some changes in particular topics and/or their schedules as the course progresses.

Timelines*

HW 1:	Assigned: 08 Sep	Due: 15 Sep
HW 2:	Assigned: 22 Sep	Due: 29 Sep
HW 3:	Assigned: 18 Oct	Due: 25 Oct
HW 4:	Assigned: 01 Nov	Due: 08 Nov
HW 5:	Assigned: 11 Nov	Due: 18 Nov

Midterm: 11 October (Tuesday)

Group Activities: Three group activities in total (once a month). They should be completed in Feb, Mar and April.

Project / Research Evaluation: During the last week of classes.

Important note:

* It is a tentative schedule. There is a strong likelihood of these dates getting shuffled a bit based on the course progress. The **midterm** date is fixed.