MAE 598: Multi-Robot Systems

Syllabus for Fall 2023

Lecture: **Monday/Wednesday 1:30-2:45pm, SCOB 150** (Schwada Classroom Office Bldg 150)

In case you cannot attend class in person as a result of illness or possible exposure to infectious disease, you may participate in this class remotely via *ASU Sync* (see end of syllabus for details). To participate remotely, **join via Zoom at this link: (TBD)**

- Recordings of all class sessions will be posted in Canvas for all students to access for reviewing course materials.

Class Website: Course materials will be posted on the **Canvas website**, which can be accessed through MyASU or myasucourses.asu.edu. Materials to be posted include announcements, readings, lecture notes and slides, assignments and solutions, and grades. Course announcements will also be sent via email.

Instructor: **Prof. Spring Berman**

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Office Hours: **TBD** over Zoom (link TBD)
Other times by appointment (schedule by e-mail to spring.berman@asu.edu)

Course Description: Multi-robot systems are currently being developed for many applications, including environmental sensing, exploration and mapping, infrastructure inspection, disaster response, agriculture, and logistics. This course combines seminar-style discussions of research on multi-robot systems with instruction on the theoretical foundations of this research. Students will complete homework assignments to gain practice using the techniques taught in class, and they will have the opportunity to further explore a particular course topic in a final project.

Enrollment Requirements: Students should be familiar with the fundamentals of linear algebra, differential equations, dynamical systems, control theory, probability theory, and MATLAB. Supplementary materials will be provided on these topics.

Course Objectives:

- Students will learn approaches to modeling, analyzing, and controlling multi-robot systems for a variety of objectives using stochastic processes, graph theoretic methods, geometric representations, dynamical systems theory, control theory, and optimization techniques.
- Students will become familiar with key research in the field of multi-robot systems that has used these approaches to develop theoretical foundations of the field and has applied them in practice.
- Students will use MATLAB to solve problems throughout the course (MATLAB is available from ASU My Apps: https://myapps.asu.edu).

Course Readings:

The course is divided into the following **modules**, with the following **sample readings** (additional assigned and optional readings will also be provided). Readings will include research publications, survey papers, lecture notes, and sections from (free) texts that are available online.

Module 1: Multi-robot systems applications, control architectures, state-of-the-art, and open challenges

- Schranz, Melanie, Martin Umlauft, Micha Sende, and Wilfried Elmenreich. "Swarm robotic behaviors and current applications." *Frontiers in Robotics and AI* 7 (2020): 36.
- Sections 53.1-53.5 of Parker, Lynne E., Daniela Rus, and Gaurav S. Sukhatme. "Multiple mobile robot systems." *Springer Handbook of Robotics* (2016): 1335-1384.

Module 2: Stochastic process and mean-field models for task allocation, assembly, and coverage

- Sections 2.1.1-2.1.3, 2.2, 2.4.1-2.4.2, 2.4.5, 2.7, 4.1, 4.2, 4.4.1-4.4.3, and 4.4.6-4.4.7 of "Lecture Notes on Mathematical Systems Biology," by Eduardo Sontag, 2022. Available here
- Correll, Nikolaus, and Alcherio Martinoli. "Multirobot inspection of industrial machinery." *IEEE Robotics & Automation Magazine* 16.1 (2009): 103-112.

Module 3: Graph-based network models for consensus behaviors such as flocking and formation control

- Ch. 1, Ch. 2 until 2.4.1, Ch. 3 until 3.3, and Ch. 4 until 4.3 of Graph Theoretic Methods in Multiagent Networks, by Mehran Mesbahi and Magnus Egerstedt, 2010. Available through the ASU Libraries website, https://lib.asu.edu/
- Ren, Wei, Randal W. Beard, and Ella M. Atkins. "Information consensus in multivehicle cooperative control." *IEEE Control Systems Magazine* 27.2 (2007): 71-82.

Module 4: Potential field-based control for navigation, coverage, and shape generation

- Sections 8.1 and 8.4 of Planning Algorithms, by Steven LaValle, 2006. Available at: http://lavalle.pl/planning/
- Rimon, Elon, and Daniel E. Koditschek. "Exact robot navigation using artificial potential functions." *IEEE Transactions on Robotics and Automation* 8.5 (1992): 501-518.

Module 5: Optimization for network connectivity control, collision avoidance, and fast task allocation

- Sections 1.1-1.4, 2.1-2.2, 2.3.1-2.3.2, 2.4.1, 3.1.1-3.1.5, 4.1.1-4.1.2, 4.2.1-4.2.2, 4.3 before 4.3.1, 4.4 before 4.4.1, and 4.6 through 4.6.2 of Convex Optimization, by Stephen Boyd and Lieven Vandenburghe, 2004. Available at: http://web.stanford.edu/~boyd/cvxbook/
- Ames, Aaron D., Samuel Coogan, Magnus Egerstedt, Gennaro Notomista, Koushil Sreenath, and Paulo Tabuada. "Control barrier functions: Theory and applications." In *2019 18th European Control Conference (ECC)*, pp. 3420-3431.

Module 6: Geometric representations for motion coordination, coverage, and shape control

- Martinez, Sonia, Jorge Cortes, and Francesco Bullo. "Motion coordination with distributed information." *IEEE Control Systems Magazine* 27.4 (2007): 75-88.
- Michael, Nathan, Jonathan Fink, and Vijay Kumar. "Controlling a team of ground robots via an aerial robot." *2007 IEEE/RSJ International Conference on Intelligent Robots and Systems*.

Module 7: Strategies for exploration, generating metric and topological maps, and target tracking

- Thrun, Sebastian. "Robotic Mapping: A Survey." (2002).
- Ramachandran, Ragesh K., Zahi Kakish, and Spring Berman. "Information correlated Lévy walk exploration and distributed mapping using a swarm of robots." *IEEE Transactions on Robotics* 36.5 (2020): 1422-1441.

Module 8: Control strategies for collective object transport and manipulation

- Chen, Jianing, Mevlin Gauci, Wei Li, Andreas Kolling, & Roderich Gross. "Occlusion-based cooperative transport with a swarm of miniature mobile robots." *IEEE Transactions on Robotics* 31.2 (2015): 307-321.
- Wang, Zijian, and Mac Schwager. "Multi-robot manipulation with no communication using only local measurements." *2015 54th IEEE Conference on Decision and Control (CDC).*

Module 9: Control strategies for collective construction tasks

- Soleymani, Touraj, Vito Trianni, Michael Bonani, Francesco Mondada, & Marco Dorigo. "Bio-inspired construction with mobile robots and compliant pockets." *Robotics and Autonomous Systems* 74 (2015): 340-350.
- Deng, Yawen, Yiwen Hua, Nils Napp, & Kirstin Petersen. "A compiler for scalable construction by the TERMES robot collective." *Robotics and Autonomous Systems* 121 (2019): 103240.

Module 10: Control strategies for self-assembly and excavation

- Klavins, Eric. "Programmable self-assembly." *IEEE Control Systems Magazine* 27.4 (2007): 43-56
- Rubenstein, Michael, Alejandro Cornejo, and Radhika Nagpal. "Programmable self-assembly in a thousand-robot swarm." *Science* 345.6198 (2014): 795-799.

Module 11: Applications in current research areas (e.g., soft robotics, micro-nanorobotics, autonomous vehicle coordination); ethical, legal, and societal issues

- Yang, Lidong, and Li Zhang. "Motion control in magnetic microrobotics: From individual and multiple robots to swarms." *Annual Review of Control, Robotics, and Autonomous Systems* 4 (2021): 509-534.
- Lesch, Veronika, Martin Breitbach, Michele Segata, Christian Becker, Samuel Kounev, and Christian Krupitzer. "An overview on approaches for coordination of platoons." *IEEE Transactions on Intelligent Transportation Systems* 23.8 (2021): 10049-10065.

Additional texts available online:

- Distributed Control of Robotic Networks, by Francesco Bullo, Jorge Cortes, and Sonia Martinez, 2009. Available through the ASU Libraries website, https://lib.asu.edu/
- Distributed Consensus in Multi-vehicle Cooperative Control: Theory and Applications, by Wei Ren and Randal Beard, 2008. Available through the ASU Libraries website, https://lib.asu.edu/

Homework: There will be about 4 homework assignments throughout the semester, which will provide opportunities to practice applying the tools and techniques taught in class and simulating multi-robot systems in MATLAB. Homework should be submitted **on Canvas** by the given due date and time. To submit your homework, scan it and save it as a **single PDF file** (for example, using a CamScanner app), and upload it on Canvas.

Final Project: Students will complete a final project on a topic of their choosing that makes use of the theoretical material taught in the course. Students may work alone on the project or in teams of two to four students. The project should incorporate a mathematical model of a multi-robot system, analysis of the model properties, and validation in simulation and/or experiments. The student(s) must describe the work in a detailed final paper **(see end of this document for guidelines)**. Students who team up must scale the scope of their project appropriately and state the contribution of each team member. Students will first submit a project proposal to the instructor and receive feedback before they begin their project.

Grading Policy:

- Students have **one week** from the day that their assignment is graded to contact the instructor regarding its grading. After the one-week period, no grading inquiry will be considered. Please note that by contesting the grading of an assignment, you are agreeing that the entire assignment is subject to being re-graded.
- Students are responsible for checking the Canvas website to make sure that it has the correct grade information.
- **Grade of Incomplete:** An “incomplete” may be awarded only in cases when a student, who is otherwise performing satisfactorily, cannot complete final course requirements, such as the final exam or final assignment, due to circumstances beyond the student’s control (such as illness or family emergency). Such circumstances must be documented. Incompletes will be approved only within the last one or two weeks of the semester. Incompletes cannot be requested after the time of the scheduled final exam for the course. To request a grade of incomplete, the student must formally apply to the instructor using the university’s “Incomplete Grade Request” form. Requests must be submitted to the student’s advisor prior to the final grade due date and are subject to final approval by the program.

Composition of course grade:

Homework assignments: 45%

Final project: 55%

Letter grade rubric:

(Note: these are approximate boundaries between grades)

A+:	≥ 95
A:	≥ 85 and < 95
A-:	≥ 80 and < 85
B+:	≥ 77.5 and < 80
B:	≥ 72.5 and < 77.5
B-:	≥ 70 and < 72.5
C+:	≥ 67.5 and < 70
C:	≥ 60 and < 67.5
D:	≥ 50 and < 60
E:	< 50

Academic Integrity Policy:

Students in this class must adhere to ASU's academic integrity policy, which can be found at https://provost.asu.edu/academic-integrity/policy). Students are responsible for reviewing this policy and understanding each of the areas in which academic dishonesty can occur. In addition, all engineering students are expected to adhere to the ASU Academic Integrity Honor Code. All academic integrity violations are reported to the Fulton Schools of Engineering Academic Integrity Office (AIO). The AIO maintains record of all violations and has access to academic integrity violations committed in all other ASU college/schools.

Specific academic integrity announcements for this class:

- **Group homework is not allowed.** This also applies to assignments that require programming: students may not write and submit multiple copies of communal code. While students may discuss homework assignments with each other, the work that each student submits must be entirely their own. Plagiarism is the submission of unreferenced content that was not the product of your original thought but which you are claiming as your own. By submitting an assignment with only your name on it, you are claiming that the content is entirely your original work.
- Direct copying of others' assignments, copying from internet sources (e.g., for the final project), allowing others to copy your work, copying resources from previous semesters, or using solution manuals are **academic integrity violations**, and recommended sanctions for these violations will be a final grade of ***E*** for this course.

Absence Policies and Extensions on Graded Assignments:

- Students will be given the opportunity to turn in graded assignments at an agreed-upon date that is later than the posted due date, but before the solutions to the assignment are posted on Canvas, in the event that they fall ill or have an excused absence related to one of the following: (1) a university-sanctioned event [ACD 304-02]; (2) religious holidays [ACD 304-04; a list can be found here https://eoss.asu.edu/cora/holidays]; (3) work performed in the line-of-duty [SSM 201-18]; and (4) illness, quarantine or self-isolation related to illness as documented by a health professional.
- Anticipated absences for university-sanctioned events, religious holidays, or line-of-duty activity should be communicated to the instructor by email at least 3 days before the expected absence.
- Absences for illness, quarantine or self-isolation related to illness should be documented by a health professional and communicated to the instructor as soon as possible by email.

Policies Regarding Expected Classroom Behavior:

- For your safety and that of your classmates and instructors, ASU recommends that students and instructors properly wear face coverings over the nose and mouth while in classrooms. Those with symptoms, a positive test, or exposure to someone with COVID-19 should follow CDC guidelines and wear a face covering if in public. Your commitment to the ASU community is greatly appreciated.
- Cell phones should be turned off during class to avoid causing distractions. Laptops, tablets, etc. may be used only for course-related use, such as note-taking or accessing Zoom. The use of recording devices is not permitted during class.

- If you join class over Zoom, please remain muted unless you are asking a question or otherwise participating in class. You can use the Zoom chat window to ask questions, write comments, or share links that are relevant to the class topic. You may leave your video camera on or off.

Policy against threatening behavior, per the Student Services Manual: Students, faculty, staff, and other individuals do not have an unqualified right of access to university grounds, property, or services (see SSM 104-02). Interfering with the peaceful conduct of university-related business or activities or remaining on campus grounds after a request to leave may be considered a crime. All incidents and allegations of violent or threatening conduct by an ASU student (whether on- or off-campus) must be reported to the ASU Police Department (ASU PD) and the Office of the Dean of Students.

Disability Accommodations: Suitable accommodations are made for students having disabilities. Students needing accommodations must register with the ASU Student Accessibility and Inclusive Learning Services and provide documentation of that registration to the instructor. Students should communicate the need for an accommodation in enough time for it to be properly arranged. See ACD 304-08 Classroom and Testing Accommodations for Students with Disabilities.

Faculty Recording of Class Sessions: Faculty may record class meetings to make an archived recording available to enrolled students, instructors, or support personnel. Creation of recordings for groups beyond these requires consent from students who are recorded.

Student Copyright Responsibilities:

- Students must refrain from uploading to any course shell, discussion board, or website used by the course instructor or other course forum, material that is not the student's original work, unless the student first complies with all applicable copyright laws; faculty members reserve the right to delete materials on the grounds of suspected copyright infringement.
- The contents of this course, including lectures and other instructional materials, are copyrighted materials. Students may not share outside the class, including uploading, selling or distributing course content or notes taken during the conduct of the course. Any recording of class sessions is authorized only for the use of students enrolled in this course during their enrollment in this course. Recordings and excerpts of recordings may not be distributed to others. (See ACD 304–06, "Commercial Note Taking Services" and ABOR Policy 5-308 F.14 for more information).

Harassment and Sexual Discrimination:

Arizona State University is committed to providing an environment free of discrimination, harassment, or retaliation for the entire university community, including all students, faculty members, staff employees, and guests. ASU expressly prohibits discrimination, harassment, and retaliation by employees, students, contractors, or agents of the university based on any protected status: race, color, religion, sex, national origin, age, disability, veteran status, sexual orientation, gender identity, and genetic information.

Title IX is a federal law that provides that no person be excluded on the basis of sex from participation in, be denied benefits of, or be subjected to discrimination under any education program or activity. Both Title IX and university policy make clear that sexual violence and harassment based on sex is prohibited. An individual who believes they have been subjected to sexual violence or harassed on the basis of sex can seek support, including counseling and academic support, from the university. If you or someone you know has been harassed on the basis of sex or sexually assaulted, you can find information and resources at https://sexualviolenceprevention.asu.edu/faqs.

As a mandated reporter, I am obligated to report any information I become aware of regarding alleged acts of sexual discrimination, including sexual violence and dating violence. ASU Counseling Services, https://eoss.asu.edu/counseling is available if you wish to discuss any concerns confidentially and privately. ASU online students may access 360 Life Services, https://goto.asuonline.asu.edu/success/online-resources.html.

ASU Sync Requirements:

ASU Sync is a technology-enhanced approach, designed to meet the dynamic needs of the class. It enables students to learn remotely through live class lectures, discussions, study groups and/or tutoring. You can find out more information at: https://provost.asu.edu/sync/students

You are encouraged to use a PC or Apple laptop, or desktop equipped with a built-in or standalone webcam. You will need an internet connection that can effectively stream live broadcasts (e.g. 3G, 4G, Cable or DSL Wifi). ASU Sync requires:

- A web browser (Chrome, Mozilla Firefox, or Safari)
- Adobe Acrobat Reader (free)
- Webcam, microphone, headset/earbuds, and speaker
- Microsoft Office (Microsoft 365 is free for all currently-enrolled ASU students)
- Reliable broadband internet connection (DSL or cable) to stream videos.

Other notes: Information in this syllabus, other than grading and absence policies, may be subject to change with reasonable advance notice.

Guidelines for MAE 598 Multi-Robot Systems Final Project Report

Fall 2023

Total possible score: **150 points (+3 extra credit points)**

Total possible score with minimum requirements: **135 points**

- This corresponds to a grade of (135/150)*100 = **90%**
- Recall from the syllabus that an **A** grade is in the range **[85%, 95%)**

General guidelines:

- The report may be written in LaTeX, Word, or whatever format you are comfortable with.
- Any references that you cite can be (but do not have to be) references that you cited in your literature review (Assignment 1).
- **The template for the report is on the next 2 pages.**

Guidelines for team projects:

- **Submission:** Only one of the team members should submit the report, and any associated files, to the **Final Course Project Assignment Page** on Canvas. The other team member(s) should post a comment on their own submission page for the assignment with the name of the team member who has submitted the report and files.
- **Division of labor:** Each of the team members should contribute approximately equal amounts of the report material. Sections II-IV can be scaled up accordingly; for example, each team member can define one of several models in Section II and analyze two properties of their model in Section III. Each team member must *at least* contribute to Section III (Analysis) *or* Section IV (Validation). In the report, identify the team member who completed each part in Sections II-IV.
- **Grading:** The report will be assigned a single score out of 150 points. All team members will receive this score if they each contributed approximately equal amounts of the report material, and the report meets (and does not exceed) the minimum requirements. Only team members who contributed material *beyond* the minimum requirements (developing a new model, designing a controller, using a multi-robot simulator or real robots for validation) will receive the extra points associated with those parts. Team members who contributed less than an approximately equal amount of the report material will receive a point deduction that corresponds to the deficiency in their contribution.

Project Title

Name(s) of student or team members

I. Abstract

- Up to **3 points**

Guidelines:

- Similar to an abstract of a conference or journal paper
- 200 – 300 words long (closer to 200 words for individual projects, closer to 300 words for team projects)

Describe the type of multi-robot behavior that you investigate in the project and potential applications of this behavior for multi-robot systems in practice. State the type of model(s) that you use to describe the behavior, the particular properties of the behavior that you analyze (and control, if you choose to do so), and the analysis (and control) techniques that you apply. Briefly describe and summarize the results of the simulations or experiments that you conducted to validate your analysis.

II. Mathematical Model

- Up to **32 points** if you use an existing model of the behavior. Up to **3 additional points** if you expand upon an existing model or develop your own model using the techniques covered in class.

Describe the multi-robot behavior that you are investigating and a hypothetical scenario in which you are applying it so solve a particular problem. State all assumptions and constraints; for instance, the robots' sensing and communication capabilities, the information that the robots have access to and how they acquire it, and the properties of the environment (e.g., bounded or unbounded, whether it contains obstacles, the geometric properties of any obstacles if known). Define all variables and parameters of your model, both in text and in figures (e.g., a diagram with coordinate systems and the definitions of inter-robot distances and sensing ranges). Explain why the assumptions, constraints, variables, and parameters are realistic for your hypothetical scenario. Finally, define the mathematical model of the collective behavior, and cite at least 2 references that introduced the model that you are using, or a model on which your model is based.

III. Theoretical Analysis

- Up to **50 points** if you prove 2 properties of the model. Up to **6 additional points** if you design a controller for the model to achieve a desired collective behavior.

Examples of properties that you can prove: the model's equilibrium state, largest invariance set, stability characteristics (e.g., asymptotically stable/marginally stable), and convergence rate to equilibrium. Show your calculations in detail. Cite at least 3 references that describe the analytical techniques that you use.

IV. Validation in Simulations and/or Experiments

- Up to **50 points** if you develop simulations in MATLAB. Up to **6 additional points** if you develop simulations in one of the multi-robot simulators listed on the page **Simulators for multi-robot systems** in Canvas. Up to **9 additional points (3 extra credit points)** if you run experiments with actual robotic hardware.

Validate the model properties that you proved in Section III using either simulations or experiments of the multi-robot behavior. Present plots of your results and describe your conclusions from the plots. Create videos of your simulations or experiments, and either include the video files with your submission, or include a link to the videos in your report. Include the code that you used to run your simulations or experiments with your submission, either as an Appendix or as separate files.