SYLLABUS 2021

Course Title: Principles of Mobile Robotics
Course Number: ABE 424/ECE 498
Semester: Spring 2021
Classroom: ONLINE (depending on campus preference)
Class Time (online): Tuesday Thursday 11:00 AM - 12:0 AM
Lab time (online): Wednesday 9:00 AM-10:30 AM

1 Instructor

Asst. Prof. Girish Chowdhary
ABE Office: 376 Agricultural Sciences and Engineering Building (AESB)
CSL Office: 150 CSL (I will be in CSL office on Tuesday to Thursday most weeks)
Office Hours: One hour before and after the class, come to my office or we hang out after the class. In the days of social-distancing, all office hours will be on zoom online.
Phone: (217) 300-3952
Email: girishc@illinois.edu

Instructor's Zoom room: Details posted in Compass

Open course website: http://daslab.illinois.edu/courses.html#abe424

Piazza: https://piazza.com/class/keecoo8z75q572

We are also on Compass, which is the main mechanism for submitting homeworks etc.

2 Course Description

The objective of this course is to prepare students in understanding the foundational principles of mobile robotics, so that they are capable of designing system architectures, algorithms, and software for autonomous aerial and ground mobile robots. The course will cover foundational aspects of the three pillars of autonomous mobile robotics: Perception and sensing, Motion Control, and Planning, and bring everything together through labs involving Ground robots and flying Unmanned Aircraft (Drones).

3 Texts

The primary text for the course is: 1. Siegwart et al., Autonomous Mobile Robots (available in UIUC library), however, this course will draw from a number of texts, in addition to notes supplied by the instructor. I do not expect that you will be purchasing all of these texts, but if you are interested in building a Mobile Robotics library, these texts will be the right ones to invest in. I will provide scans and summaries where appropriate on Piazza. In addition, a number of papers are included in the required reading.

The primary texts utilized are:

1. **Siegwart et al., Autonomous Mobile Robots (available in UIUC library)**
2. Kuipers, Quaternions and Rotation Sequences (available in UIUC library)
3. Farrell, Aided Navigation, GPS with high-rate Sensors
4. Instructor notes

Optional additional reading:

5. Kelly, Mobile Robotics: Mathematics, Models, and Methods
6. Dudek and Jenkin, Computational Principles of Mobile Robotics
7. Thrun et al., Probabilistic Robotics

4 Course Motivation

This section of the syllabus explains the motivation behind the creation of this course and what you can expect to get out of it.

Robots are systems that perceive and understand the world around them and are capable of navigating the world or manipulating objects to perform tasks. The last century has seen an unprecedented growth in manufacturing productivity and quality largely due to the advent of factory-based robots. These robots accomplish complex manufacturing and assembly tasks in structured and highly controlled indoor environments. In contrast, mobile robots can maneuver themselves to locations where tasks need to be done. This opens the possibility of tackling a much broader variety of tasks in the real-world, outdoor, or loosely structured environments, which are not controlled, and in some cases can be harsh, full of uncertainty, and dynamically changing. The next age in robotics will be enabled by rapid and profound advances in mobile robotics. The objective of this course is to prepare students in the foundations of mathematical principles, computational algorithms, and systems architecture aspects to enable them to design the next generation of mobile and outdoor robots that accomplish complex tasks in the face of high level of uncertainty.

We are already seeing exciting developments in the mobile robotics. Autonomous driving cars; home-cleaning robots; warehouse robots; GPS enabled precision agricultural autonomous seeders, harvesters and sprayers; extraterrestrial rovers; and Unmanned Aerial Vehicles are but some examples of field robots. As the century progresses, we will see mobile robots enabling a vast array of exciting applications in domains where fixed robots have not yet had an impact.

In all of these and other emerging applications, the key enabling technology will leverage seamless integration of Cyber and Physical components in compact and self-sufficient robots that are able to communicate and work with each-other and humans. Cyber components include software, embedded computers, sensors, and other electronic and computational artifacts; while physical components include hardware (cars, airplanes, power lines) that is subject to the rules of physics (dynamics, kinematics, elctromechanics, fluid flows).

Robotic cyber-physical systems (CPS) are expected to achieve the following:

- Understand, perceive, and model the environment in which they operate
- Make real-time decisions to meet higher level objectives
- Ensure the safety of the system and its stake-holders
- Operate robustly in a wide variety of environments
- Collaborate with other systems

This course has been created to provide an introduction to the underlying scientific and engineering principles for the design and automation of mobile field robots.

5 Learning Outcomes

This 400 level course will prepare students in three principle aspects of field robotics: Perception, Motion Control, and Mission Planning. Our focus will be on mobile robots that, as such, we will focus less on manipulation with armed robots (for this purpose, the course ECE 470 is suggested, but not required), but focus more on dynamic modeling of nonholonomic systems, locomotion, algorithms for perception using multiple sensors, Simultaneous Localization and Mapping, motion control, and foundations of planning.

The specific learning outcomes are:

1. Be able to identify what makes mobile robotics challenging and exciting, for the robotics community, and the students themselves
2. Provide a taxonomy of different types of mobile robotic systems and methods of locomotion
3. Be able to construct dynamic model of holonomic and nonholonomic mobile robots
4. Be able to explain the workings of different sensor systems utilized for mobile robots, construct their mathematical models, and emulate their behaviors in software
5. Be able to create sensor fusion algorithms and software through Bayesian filtering.
6. Be able to derive Kalman Filters from scratch and construct approximation or sampling based filters for nonlinear systems
7. Construct Kalman filtering based GPS-INS algorithms and architectures, and other variants of multi-sensor fusion algorithms that combine high-rate inertial and encoder sensing with low-rate exteroperceptive sensors
8. Describe basic architectures and principles of Simultaneous Localization and Mapping (SLAM) algorithms
9. Identify different types of SLAM algorithms and construct a taxonomy of SLAM algorithms.

10. Engage in specific case-studies of SLAM: LIDAR-inertial SLAM, visual-inertial SLAM, depth-fusion based SLAM, 3-D reconstruction
11. Be able to create motion control algorithms of aerial and wheeled ground robots using basic linear methods as well as adaptive and optimal control in the presence of nonholonomic constraints
12. Create basic path planning algorithms using PRM, RRT, RRT*, and MDPs
13. Describe the three foundational elements (perception, planning, and control) of mobile robot autonomy architectures, and identify algorithmic elements using examples from agricultural robotics, home robotics, hospital robotics, and autonomous driving.
14. Describe the 5 levels of autonomy and identify sensing, architectures, algorithms, and software barriers to advancing the levels of autonomy for different mobile robotic systems

Specific Lab-based learning outcomes

15. Be able to program autonomous data collection and task missions on mobile robotic systems using GPS based waypoints and spatial task-specifications
16. Design and implement robot software with the Robot Operating System (ROS) middleware and python
17. Obtain, plot, and analyze data collected from mobile robots using ROS
18. Create GPS-INS error state Kalman filter software and validate it using data from real robots
19. Create elements of SLAM software such as edge detection, corner detection, and map adjustments
20. Describe different algorithms for SLAM, motion control, and planning software libraries and know how to use them through ROS

All of our development will be theoretically motivated, but in this course we will place a particular emphasis on fundamental understanding of principles and their interrelations, synthesis of algorithms, and development of high-quality software. The latter will be executed through a set of laboratories that emphasize core content taught in the course, utilize ROS, and expose the students to the entire mission-cycles of mobile robots, from obtaining data, to improving software, to evaluating the improvements.

At the end of this course, you should be able to design and create algorithms and software systems for mobile robots. There is a strong emphasis in this course on algorithmic synthesis and deep understanding of underlying mathematical and computational principles. We expect you will have built a strong foundation for pursuing graduate level courses in autonomous decision making, control, sensing, and machine learning, or that you will be ready to join industry in leading positions to create the next generation of robotic systems.

Graduate standing: The material covered in this course will be appropriate for senior level undergraduates, and graduate students interested in robotics, especially to those who are not familiar with mobile and/or field robotics. This course is available to upper level undergraduates, but is also appropriate for beginning graduate students in robotics. The course requires a knowledge of differential equations, probability and statistics, linear algebra and programming skills. Graduate and undergraduate students will be required to submit the same assignments and be graded in a similar manner.

6 Course Prerequisites

The specific prerequisites are: MATH 221, MATH 225, and MATH 285 , or ABE 415, or ABE 440, IE 300, or STAT 400 or equivalent, CS 125 or equivalent. Graduate standing is sufficient to waive prerequisite requirements for graduate students. Other cases will be evaluated on a case-by-case basis by the instructor. In general, students are expected to have taken introductory differential equations, introduction to probability and statistics, linear algebra, and software programming.

Programming: An introductory knowledge of programming is essential for this course. Python is the language of choice, however, for certain assignments, you may choose any programming language that you are comfortable with for the problem sets and the laboratories. We will provide resources for getting comfortable with Python and ROS. Since we will use ROS, it is useful for you to be also familiar with Linux, although we will provide a quick primer. Most of the templates provided by the instructor will be in Python. Furthermore, we might sometimes use code from online repositories, which may be in C or C++. This is not required, but if you have taken CS 225 (data structures) or equivalent you would meet or exceed the programming requirements.

7 Course Outline

1. **Module 1 Introduction to Mobile Robotics**
    a. What is a mobile robot
    b. What makes mobile robotics challenging and exciting
    c. Applications of mobile robotics
    d. Lab: Visiting the field and collecting aerial and ground robot data in autonomous modes
2. **Module 1.5 Fundamental mathematical principles**:
    a. Mathematical notation, norms, vector spaces, and differential equations
    b. Review of Matrix theory
    c. Review of Coordinate frames and rotational transformations
    d. Systems theory, stability, controllability, observability of linear and nonlinear systems
    e. Probability Theory
3. **Module 2 Dynamics of Mobile robots**
    a. Coordinate transformations with Euler angles
    b. The space of rotation matrices SO(2) and SO(3)
    c. Quaternions as a way of representing and working with rotations
    d. General 6 DOF Kinematic and Dynamics equations with quaternions

    e. Holonomic dynamics: Case study: Aerial Multirotor robots (drones)
    f. Nonholonomic dynamics: Case study: Independent all-wheel drive wheeled robots
    g. Vignettes: walking robots
    h. Lab: Understanding the limitations and capabilities of different mechanisms of locomotion for mobile robots, mathematical modeling and analysis of a quadrotor and a ground rover robots
4. **Module 3 Principles of robot perception in the wild**
    a. Principles of sensing
        i. Dead-reckoning: Intuition and foundations
        ii. Mathematical underpinnings of dead-reckoning
        iii. Global frame localization: Mathematics of Global positioning system and satellite navigation
        iv. Interoceptive sensing: Systems and mathematical models of Inertial sensors
        v. Interoceptive sensing: Systems and mathematical models of Encoders
        vi. Passive exteroceptive sensing: Principles of cameras as sensors and machine vision
        vii. Active exteroceptive sensing: Radiation based sensors (Radars, Lidars)
        viii. Vignettes: UWB and VICON based restricted-area positioning for mobile robots: The Intel drone show
        ix. Lab: Collecting multi-sensor data from ground robots and analyzing it with ROS
    b. Kalman Filtering and Bayesian data fusion
        i. Bayes principle and the Chapman-Kolmogorov Equation
        ii. Optimal filtering problem with Gaussian noise and linear dynamics (Kalman Filters)
        iii. Extended Kalman filters, using point based linearization to deal with nonlinear dynamics
        iv. Vignette: Particle filters and unscented Kalman filter
    c. GPS-INS sensor fusion with Extended Kalman Filters
        i. Process and noise models
        ii. Filter formulation
        iii. LAB: Develop software for GPS-INS fusion with EKF given data
    d. Simultaneous Localization and Mapping (SLAM)
        i. Introduction to SLAM
        ii. Key-frame matching solution
        iii. Bundle adjustment
        iv. Posing SLAM as an optimization problem
        v. LAB: SLAM with LIDAR
        vi. Vignettes: A taxonomy of SLAM algorithms, from dense SLAM to sparse SLAM
5. **Module 4 Principles of robot motion control**
    a. Overview of linear systems and PID controllers

        i. State-space models
        ii. Observability and controllability
        iii. Limitations of linear control for mobile robots
    b. Nonlinear control
        i. Lyapunov stability and nonlinear dynamics of mobile robots
        ii. Introduction to Model Predictive Control
    c. Case study: Waypoint navigation for aerial drones
    d. Case study: Motion control of a wheeled robot
    e. Vignette: Model Reference Adaptive Control of quadrotors
    f. Lab: Motion control of a wheeled robot
6. **Module 5: Where to from here?**
    a. Planning algorithms
        i. Foundations of path planning: PRM, RRT, and RRT*
        ii. Software architectures for higher-level decision making
        iii. Levels of Autonomy
    b. Discussion of trends in mobile robotics
    c. What courses can you take from here if you are interested in:
        i. Perception, machine vision, pattern recognition, and learning
        ii. AI for robotics
        iii. Control of nonlinear and constrained mobile robots
    d. Multi-robot autonomy
    e. Vignettes: Groups in class prepare presentations on deployed robotic systems

8 Grading

Grades will be determined based on demonstrated proficiency on problem sets, laboratories, a project, and midterm and final examination. Problem sets involve mathematical problem formulation, analysis, and software development in Python or where applicable, programming language of student's choice. The points associated with each graded event are shown below along with the associated letter grade.

Point Breakout:

Problem Sets	= 350 points
Labs (3)	= 300 points
Midterm 1	= 100 points
Midterm 2	= 100 points
Final Exam	= 150 points
Total	**= 1000 points**

Grading Scale:

A+	= 960-1000 Total Points
A	= 900-960 Total Points
A-	= 880-900 Total Points
B+	= 850-880 Total Points
B	= 800-850 Total Points
B-	= 780-800 Total Points
C, C-, C+	= 700-780 Total Points
D, D-, D+	= 600-699 Total Points
F	= 0-599 Total Points

Occasionally, students will be offered the opportunity to obtain extra credit points. These points are added to the student's total while the total points for the course remains at 1000.

Late deliverable policy:
One and only one deliverable can be turned in late by 2 days. For every other deliverable, and past the 2 days for the first late deliverable, you will be penalized 20% per day of grade earned for that deliverable.

9 Policies and Ethics

Academic Integrity
Please review and reflect on the academic integrity policy of the University of Illinois, http://studentcode.illinois.edu/article1_part4_1-401.html, to which we subscribe. By turning in materials for review, you certify that all work presented is your own and has been done by you independently, or as a member of a designated group for group assignments.
If, in the course of your writing, you use the words or ideas of another writer, proper acknowledgement must be given (using IEEE or other appropriate citation style of your preference). Not to do so is to commit plagiarism, a form of academic dishonesty. If you are not absolutely clear on what constitutes plagiarism and how to cite sources appropriately, now is the time to learn. Please ask me!

Please be aware that the consequences for plagiarism or other forms of academic dishonesty will be severe. Students who violate university standards of academic integrity are subject to disciplinary action, including a reduced grade, failure in the course, and suspension or dismissal from the University.

Criteria for grading homework assignments include (but are not limited to) creativity and the amount of original work demonstrated in the assignment. However, students are permitted to use and adapt the work of others, provided that the following guidelines are followed:

- Use of other people's material must not infringe the copyright of the original author, nor violate the terms of any licensing agreement. Know and respect the principles of fair use with respect to copyrighted material.

- Students must scrupulously attribute the original source and author of whatever material has been adapted for the assignment. Summarize the changes or adaptations that have been made. Make plain how much of the assignment represents original work.

Policy on Cheating: Cheating constitutes to using material from fellow students or the internet without proper attribution. You are welcomed and encourage to use the internet as a source of knowledge, but any use of internet obtained material, including code must be attributed. Any student determined to have cheated on a homework will receive zero credit for the entire semester's homework. Any student determined to have cheated in lab or exams, will receive zero credit for all of the labs or exams.

Statement of Inclusion http://www.inclusiveillinois.illinois.edu/mission.html As the state's premier public university, the University of Illinois at Urbana-Champaign's core mission is to serve the interests of the diverse people of the state of Illinois and beyond. The institution thus values inclusion and a pluralistic learning and research environment, one which we respect the varied perspectives and lived experiences of a diverse community and global workforce. We support diversity of worldviews, histories, and cultural knowledge across a range of social groups including race, ethnicity, gender identity, sexual orientation, abilities, economic class, religion, and their intersections.

Accessibly Statement   *Text from Graduate College website*   To obtain accessibility-related academic adjustments and/or auxiliary aids, students with disabilities must contact the course instructor and the Disability Resources and Educational Services (DRES) as soon as possible. To contact DRES you may visit 1207 S. Oak St., Champaign, call 333-4603 (V/TTY), or e-mail a message to disability@uiuc.edu.

Per guidelines from the Chancellor's Committee on Access and Accommodations (http://ccaa.dres.illinois.edu/guidelines.php), this statement must be included: This syllabus may be obtained in alternative formats upon request. Please contact the instructor.

Required Syllabus statements:
Academic Integrity
The University of Illinois at Urbana-Champaign *Student Code* should also be considered as a part of this syllabus. Students should pay particular attention to Article 1, Part 4: Academic Integrity. Read the Code at the following URL: http://studentcode.illinois.edu/ .
Academic dishonesty may result in a failing grade. Every student is expected to review and abide by the Academic Integrity Policy: http://studentcode.illinois.edu/. Ignorance is not an excuse for any academic dishonesty. It is your responsibility to read this policy to avoid any misunderstanding. Do not hesitate to ask the instructor(s) if you are ever in doubt about what constitutes plagiarism, cheating, or any other breach of academic integrity.

Students with Disabilities
To obtain disability-related academic adjustments and/or auxiliary aids, students with disabilities must contact the course instructor and the Disability Resources and Educational Services (DRES) as soon as possible. To contact DRES, you may visit 1207 S. Oak St., Champaign, call 333-4603 (V/TDD), or e-mail a message to disability@uiuc.edu. http://www.disability.illinois.edu/.

Emergency Response Recommendations
Emergency response recommendations can be found at the following website: http://police.illinois.edu/emergency-preparedness/. I encourage you to review this website and the campus building floor plans website within the first 10 days of class. http://police.illinois.edu/emergency-preparedness/building-emergency-action-plans/.

Family Educational Rights and Privacy Act (FERPA)
Any student who has suppressed their directory information pursuant to *Family Educational Rights and Privacy Act* (FERPA) should self-identify to the instructor to ensure protection of the privacy of their attendance in this course. See https://registrar.illinois.edu/academic-records/ferpa/ for more information on FERPA.

Sexual Misconduct Policy and Reporting
The University of Illinois is committed to combating sexual misconduct. Faculty and staff members are required to report any instances of sexual misconduct to the University's Title IX and Disability Office. In turn, an individual with the Title IX and Disability Office will provide information about rights and options, including accommodations, support services, the campus disciplinary process, and law enforcement options.
A list of the designated University employees who, as counselors, confidential advisors, and medical professionals, do not have this reporting responsibility and can maintain confidentiality, can be found here: wecare.illinois.edu/resources/students/#confidential.
Other information about resources and reporting is available here: wecare.illinois.edu.

COVID-19 Considerations:
Following University policy, all students are required to engage in appropriate behavior to protect the health and safety of the community, including wearing a facial covering properly, maintaining social distance (at least 6 feet from others at all times), disinfecting the immediate seating area, and using hand sanitizer. Students are also required to follow the campus COVID-19 testing protocol.

Students who feel ill must not come to class.In addition, students who test positive for COVID-19 or have had an exposure that requires testing and/or quarantine must not attend class. The University will provide information to the instructor, in a manner that complies with privacy laws, about students in these latter categories. These students are judged to have excused absences for the class period and should contact the instructor via email about making up the work.

Students who fail to abide by these rules will first be asked to comply; if they refuse, they will be required to leave the classroom immediately. If a student is asked to leave the classroom, the non-compliant student will be judged to have an unexcused absence and reported to the

Office for Student Conflict Resolution for disciplinary action. Accumulation of non-compliance complaints against a student may result in dismissal from the University.

10 Organization and Course Calendar

The following calendar is tentative and subject to change

Class no	Date		Topic in class	Problem Set
1	1/26/21	M1	Welcome and field robot demos	
2	1/28/21		Welcome and Introduction to field robotics	
3	2/2/21		Preliminaries: Applications of linear algebra	PSET 1 out
4	2/4/21		Preliminaries: Linear controllers and observers	
5	2/9/21		Introduction to Quaternions	
6	2/11/21		Coordinate frames	
7	2/16/21		Quaternions	
8	2/18/21	M2	Holonomic vs non-holonomic dynamics	
9	2/23/21		Deriving equations of motion of quadrotor	PSET 1 in
10	2/25/21		Equations of motion of fixed wing aircraft	PSET 2 out
11	3/2/21		GPS	
12	3/4/21		GPS INS	
13	3/9/21		LIDAR	
14	3/11/21		Mid-Term Test 1	
15	3/16/21	M3	Introduction to KFs	PSET 2 in
16	3/18/21		Introduction to KFs	
17	3/23/21		Introduction to KFs	
18	3/25/21		Inertial Sensors	PSET 3 out
	3/30/21		GPS-INS sensor fusion: EKF formulation	
	4/1/21		GPS-INS sensor fusion: EKF formulation	
19	4/6/21		Integrating other sensors in the EKF framework	
20	4/8/21	M4	Integrating other sensors in the EKF framework	
21	4/13/21		No Lecture (Instruction break)	
22	4/15/21		SLAM	PSET 3 in
23	4/20/21		SLAM	
24	4/22/21		Mid-Term Test 2	
25	4/27/21		Motion control of wheeled robot	PSET 4 out

26	4/29/21		Mission planning and control	
27	5/4/21		Final lecture	

Lab no			
	1/27/21		No lab
	2/3/21	L1	Lab 1 intro
	2/10/21		Understanding Drones and ground robot systems
	2/17/21		No Lab (Instruction break)
	2/24/21		Processing of data from the drone flights
	3/3/21	L2	Lab 2 intro
	3/10/21		LIDAR data collection and analysis
	3/17/21		LIDAR data collection and analysis
	3/24/21		No lab (Instruction break)
	3/31/21	L3	GPS-INS fusion introduction
	4/7/21		Coding workshop
	4/14/21		Coding workshop
	4/21/21	L4	LIDAR SLAM
	4/28/21		Coding workshop
	5/5/21		Coding workshop