Manipulation, Estimation[1], and Control
16-642 Fall 2017

Meeting Times: MW 12:00pm–1:20pm, NSH1305

Course Website: CMU Canvas

Overview: This course provides an overview of the current techniques that allow robots to move around, interact with the world, and keep track of where they are. The kinematics and dynamics of electromechanical systems will be covered with a particular focus on their application to robotic arms. Some basic principles of robot control will be discussed, ranging from independent- joint PID tracking to coupled computed torque approaches. State estimation techniques including the extended Kalman filter will be covered, especially as they are used in solving common problems faced in robotics applications.

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Textbook: There is no assigned textbook for this class, however there are some books that you might find useful as reference material for various parts of the class. In particular, a more detailed treatment of the material from our lectures on Kinematics and Dynamics can be found here:

> M.W. Spong, S. Hutchinson, and M. Vidyasagar, Robot Modeling and Control, John Wiley and Sons, Inc., 2006.

A more detailed treatment of the material from our lectures on Control can be found here:

> K.J Astrom and R.M. Murray, Feedback Systems: An Introduction for Scientists and Engineers, Princeton University Press, 2008. Complete text available online at http://www.cds.caltech.edu/~murray/amwiki/index.php/Main_Page

Course Canvas: The course canvas site will be the primary means of disseminating information about the course throughout the semester. Problem sets and important announcements will be posted there. Lecture notes will be also posted to the class blackboard. In general, they will be posted within a day or two of the given lecture, however no promises are made about timeliness of the posting. Posted lecture notes are meant as supplemental material only. ***There is no substitute for coming to class and taking your own notes during lectures.***

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[1] This is a new title for 16-642, the official title is still Manipulation, Mobility, and Control

Prerequisites: There are no formal prerequisites for this class. Informally, a year of calculus, a year of programming, and familiarity with matrix algebra will greatly increase your chances of success in this class. Also helpful, but not required, is a course on classical mechanics.

Grading:

	Problem sets	60%
	Exam I	20%
	Exam II	20%

Above 90 is an A, from 80 to 90 is a B, etc. We may lower the thresholds slightly but we will not raise them.

Problem sets are due **at the beginning of class** of the posted due date. Problem sets will be handed in electronically via the blackboard. Problem sets up to 48 hours late will receive half credit. Problem sets more than 48 hours will not be accepted.

Exams There will be two in-class midterms, one on **October 18** and one on **December 6**. Details about exam rules will be given later in the semester. Missing an exam will result in a zero, unless there is a dire medical or family emergency; in such cases, you must discuss with the instructor prior to the exam. Job interviews, special courses, and other enhancing experiences, although wonderful, are not reasons to miss an exam. These tests are arranged in advance so that you can plan your schedules accordingly.

Learning Objectives:
By the end of this course, students are expected to be able to do the following:

- Simulate and analyze dynamic behavior of physical systems through ordinary differential equations and difference equations.
- Derive transfer function representation of linear systems from ordinary differential equations and difference equations using Laplace and z transforms.
- Predict qualitative and quantitative behavior of continuous and discrete time linear systems by examining transfer function poles.
- Derive single transfer function of systems composed of multiple component linear systems combined in series, parallel, and feedback configurations.
- Synthesize PID feedback controllers to achieve desired step-response characteristics.
- Analyze transient behavior of linear and nonlinear state-space systems via eigenvalues and Lyapunov theory.
- Construct state feedback controllers and state observers for linear state space systems via pole placement and linear quadratic regulator.
- Understand the Kalman filter equations, and implement extended Kalman filter for robotic state estimation and SLAM.
- Understand pose graph estimation techniques, and implement them for problems such as SLAM and vision-based odometry.

Take care of yourself. Do your best to maintain a healthy lifestyle this semester by eating well, exercising, avoiding drugs and alcohol, getting enough sleep and taking some time to relax. This will help you achieve your goals and cope with stress.

All of us benefit from support during times of struggle. You are not alone. There are many helpful resources available on campus and an important part of the college experience is learning how to ask for help. Asking for support sooner rather than later is often helpful.

If you or anyone you know experiences any academic stress, difficult life events, or feelings like anxiety or depression, we strongly encourage you to seek support. Counseling and Psychological Services (CaPS) is here to help: call 412-268-2922 and visit their website at http://www.cmu.edu/counseling/. Consider reaching out to a friend, faculty or family member you trust for help getting connected to the support that can help.

If you or someone you know is feeling suicidal or in danger of self-harm, call someone immediately, day or night:

CaPS: 412-268-2922
Re:solve Crisis Network: 888-796-8226
If the situation is life threatening, call the police:
    On campus: CMU Police: 412-268-2323
    Off campus: 911

Course Schedule (subject to change):

		Date	Lecture Topic
Robot Kinematics	M	28-Aug	**Introduction, Foundations:** course overview; task, joint, and configuration space; rotation matrices.
	W	30-Aug	**Homogeneous Transformation:** points and vectors; homogeneous matrices; basic displacements;
	M	4-Sep	**Labor Day -- No Classes**
	W	6-Sep	**Spatial Compositions:** Composing displacements; other rotation representations.
	M	11-Sep	**George Out -- No Class**
	W	13-Sep	**George Out -- No Class**
	M	18-Sep	**Kinematics:** Denavit-Hartenberg convention; the big equation; DH Example.
	W	20-Sep	**Inverse Kinematics:** Setting up the problem; four tricks; kinematic decoupling; numerical approach. **Problem Set 1 due**
	M	25-Sep	**Velocity Kinematics:** Jacobians; Inverse velocity kinematics.
	W	27-Sep	**Velocity Kinematics Cont.:** More velocity kinematics, static force-torque relationship.
Dynamics and Control	M	2-Oct	**Planar Euler Lagrange Dynamics:** EL equations; kinetic and potential energy; RP example.
	W	4-Oct	**SE(3) Euler Lagrange Dynamics:** Inertia tensor and kinetic energy; n-link manipulator cookbook method.
	M	9-Oct	**Introduction to State Space Systems:** State equations; numerical integration.
	W	11-Oct	**Linear State Space Systems:** Stability; Second order systems; controllability. **Problem Set 2 due**
	M	16-Oct	**Linear State Feedback:** Pole placement, LQR, tracking controllers.
	W	18-Oct	**Exam 1**
	M	23-Oct	**Classical Controls:** Transfer functions; state space realizations; block diagrams; step response.
	W	25-Oct	**Classical Controls (cont.):** Complex plane intuition; root locus; PID control.
	M	30-Oct	**Classical Control Examples**

Estimation	W	1-Nov	**Robotic Manipulator Control:** Independent PID loops, gravity compensation, feedback linearization, centralized control. **Problem Set 2 due**
	M	6-Nov	**Linear State Observers:** Observability; Observer derivation and design.
	W	8-Nov	**Kalman Filter prep:** discrete time systems; multivariate Gaussian distribution. **Problem Set 3 due**
	M	13-Nov	**Kalman Filter:** concept; equation derivation; extended Kalman filter; ROS packages.
	W	15-Nov	**Kalman Filter Applications:** SLAM, wheeled vehicle state estimation.
	M	20-Nov	**Bundle Adjustment Estimation:** pose graph concept; laser odometry applications; optimization packages.
	W	22-Nov	Thanksgiving (no classes)
	M	27-Nov	**Pose Graph SLAM:** Adding features to the pose graph; visual odometry; SLAM.
	W	29-Nov	**Sensor fusion / state estimation example:** Wheeled vehicle SLAM with vision, lidar, and inertial sensing. **Problem Set 4 due**
	M	4-Dec	**Class Review**
	W	6-Dec	**Exam 2**