Brandeis | GRADUATE PROFESSIONAL STUDIES

I. Course Information

Course Name: Robot Manipulation, Planning, and Control
Course Number: RBOT 250
Course Start and End Dates: January 15 - March 24, 2020
Instructor: Dr. Lekan Molu
Office Hours: TBD

Document Overview

This syllabus contains all relevant information about the course: its objectives and outcomes, the grading criteria, the texts and other materials of instruction, and of weekly topics, outcomes, assignments, and due dates.

Consider this your roadmap for the course. Please read through the syllabus carefully and feel free to share any questions that you may have. Please print a copy of this syllabus for reference.

Course Description

This course focuses on the algorithmic and mathematical concepts when dealing with robot planning, manipulation and control. Topics covered include kinematics and dynamics, as well as path planning algorithms. Simulations will be performed to test the related algorithms.

Course Outcomes

After taking this course, each student will be able to:

1. Develop planning and manipulation solutions to drive robot operation
2. Integrate perception algorithms into manipulation and planning systems
3. Use simulation to drive testing of robotic algorithms

Prerequisites

RBOT 210 or advanced knowledge of ROS; undergraduate-level experience or equivalent with object oriented programming; strong programming knowledge of Python and C++ is required; and RBOT 205 if mathematical foundational skills of admissions criteria are needed.

Recommended Texts:

- **Main Texts: Murray, R. M., Li, Z., & Sastry, S. S. (1994).** ***A Mathematical Introduction to Robotic Manipulation*. *Book*** **(Vol. 29). Free PDF preprint downloadable from, https://www.cds.caltech.edu/~murray/books/MLS/pdf/mls94-complete.pdf**
- Spong, M. W., Hutchinson, S., & Vidyasagar, M. (2012). Robot Modeling and Control. Amazon Link: https://www.amazon.com/Robot-Modeling-Control-Mark-Spong/dp/0471649902

- Secondary Text: Modern Robotics: Mechanics, Planning, and Control. Free PDF preprint downloadable from http://hades.mech.northwestern.edu/images/7/7f/MR.pdf
- Auxiliary Text: Theory of Screws: A Study in the Dynamics of a Rigid Body by Robert Stawell Ball, Dublin: Hodges, Foster, and Co., Grafton-Street (Should be downloadable via Interlibrary Loan).

Required Software: The Robot Operating System, https://www.ros.org/; A working knowledge of python and the anaconda environment. ROS from Conda installation instructions: https://medium.com/@wolfv/ros-on-conda-forge-dca6827ac4b6

Recommended Text(s) / Journals:

- Transactions on Robotics: https://ieeexplore.ieee.org/xpl/RecentIssue.jsp?punumber=8860
- The International Journal of Robotics Research: https://journals.sagepub.com/home/ijr
- The International Conference on Robotics and Automation: https://www.ieee-ras.org/conferences-workshops/fully-sponsored/icra
- IEEE/Robotics Society of Japan International Conference on Intelligent Robots and Systems (IROS): https://www.ieee-ras.org/conferences-workshops/financially-co-sponsored/iros
- Robotics and Autonomous Systems, An Elsevier Journal: https://www.journals.elsevier.com/robotics-and-autonomous-systems

Online Course Content

This course will be conducted completely online using Brandeis' LATTE site, available at http://moodle2.brandeis.edu. The site contains the course syllabus, assignments, our discussion forums, links/resources to course-related professional organizations and sites, and weekly checklists, objectives, outcomes, topic notes, self-tests, and discussion questions. Access information is emailed to enrolled participants before the start of the course. To begin participating in the course, review the Welcoming Message and the Week 1 Checklist.

Course Grading Criteria

Description of Components and Percentages

Component	Description	% Final Grade
Assignments	There will be weekly assignments to test your understanding of each week's coursework	40
Discussions/ Online Participation	You are encouraged to engage one another, ask questions about assignments, textbook materials, as well as contribute meaningful discussions that enlighten others on the discussion forum.	20
Final Project*	Each student will be expected to submit a final self-completed project of their own choosing. During the course, students are encouraged to discuss with the instructor one-on-one on what topics interest them and how they envision translating the topic into a meaningful hands-on course project.	40

Grading Criteria for Discussions/Online Participation

Discussion responses to instructor posts will be graded according to the criterion outlined below:

An exceptional post:

Provides original, substantive, and thought provoking analysis of the course material.
Is coherent and has a central thesis.
Contains properly cited references.
Is grammatically correct and contains no spelling errors.

A good post:

Contains most elements of an exceptional post, but may lack coherency and/or have a couple minor spelling/grammatical errors.

A fair post:

Provides only a surface-level analysis of the course material.
Contains properly cited references.
Contains a few grammatical and/or spelling errors

A poor post:

Provides only a surface-level analysis of the course material.
Does not properly cite references.
Contains several grammatical and/or spelling errors.

Similarly, substantive responses to peer posts will be similarly graded. In addition to the grading metric outlined above, to earn full credit the responses must (1) address the author of the post directly and highlight texts/ideas from the original post and 2) provide constructive insight (i.e. not simply "I agree/disagree with you").

II. Weekly Information & Assignment Outline

Week 1	Introduction: Robot Configurations
Objectives	● The symbolic definition of robots: Links, Joints and End-Effectors ● Robot spaces,serial and parallel robot geometries, classifications based on link components ● Open and Closed kinematic chains ● End Effectors, Connectivity Criterion: Gruebler-Kutzbach mobility condition
Outcomes	● Explain the concept of links, joints and mechanisms ● Identify the differences between open and closed kinematic chains ● Describe the classification of robots as rigid, semi-rigid or soft robot ● Describe the configuration space, state space, workspace, joint space and task space of a robot

Readings	● Robot Modeling and Control, Spong, Vidyasagar, and Hutchinson, Chapter 1 ● Structural Kinematics of In- Parallel-Actuated Robot-Arms, Hunt, K.H., Dec 1983 ● Some Mathematical Aspects of Robotics. Proceedings of Symposia in Applied Mathematics. 1990.
Assignments	● Assignment #1 (4% of Term Assignments) ● Week I Discussion Topics (2%)
Week 2	Rigid Body Motions
Objectives	● Theory of Screws: twist, wrench, pitch, axis ● Homogeneous coordinates for motion representation ● The matrix exponential and Rodrigues' formula ● Exponential Coordinates for rigid motions and twists
Outcomes	● Relate the resultant twist and screw ● Describe relation of forces acting on a rigid body with wrench ● Describe the displacement and rotation of a rigid body about a screw
Readings	● **Murray, R. M., Li, Z., & Sastry, S. S. (1994).** ***A Mathematical Introduction to Robotic Manipulation*. *Book* (Vol. 29), Chapter 2** ● A Treatise on the Theory of Screws. Sir R.S. Ball, Chapter 1 ● Screw Theory for Robotics. Jose M. Pardos-Gotors, IROS2018 Tutorial Madrid (Instructor will provide a copy of the materials)
Assignments	● Assignment #2 (4% of Term Assignments): Matlab examples of Rodrigues' formula, exponential coordinates for rigid bodies etc ● Week II Discussion Topics (2%)
Week 3	Rigid Body Motions
Objectives	● Rotational motions in R3; Homogeneous representation ● Rigid Body Velocities and Coordinate transformations ● Parameterization of Rotations: Euler angles, RPY angle and axis/angle representation ● Lie algebra and Lie groups
Outcomes	● Describe the displacement and rotation of a rigid body about a screw ● Explain rigid body transformations, rotational motions in R^3 and their properties ● Identify the transformation of a rigid body with the exponential formula and quaternions ● Explain clearly the difference between using the product of Exponentials formula and the D-H Conventions ● Develop a comprehensive understanding of screws and their applications to rigid and semi-rigid body dynamics and kinematics
Readings	● **Murray, R. M., Li, Z., & Sastry, S. S. (1994).** ***A Mathematical Introduction to Robotic Manipulation*. *Book* (Vol. 29), Chapter 2** ● A Treatise on the Theory of Screws. Sir R.S. Ball, Chapter 1
Assignments	● Assignment #3 (4% of Term Assignments) ● Week III Discussion Topics (2%)

Week 4	Manipulator Kinematics
Objectives	● Forward kinematics ● Denavit-Hartenberg Conventions ● Product of Exponentials Formula ● Screw Axes in Base Frame ● Manipulator parameterization with twists ● Screw Axes in Tool Frame ● Velocity Kinematics ● Inverse kinematics ● Decouple inverse position kinematics and inverse orientation kinematics
Outcomes	● Define the forward kinematics problem (for a general robot, rigid, semi-rigid or soft) ● Explain the inverse kinematics problem ● Given a robot configuration, decouple the inverse position kinematics from the inverse orientation kinematics ● Explain clearly the difference between using the product of Exponentials formula and the D-H Conventions
Readings	● Robot Modeling and Control, Spong, Vidyasagar, and Hutchinson, Chapter 3 ● Modern Robotics by Kevin Lynch and Frank Park, Chapter 4 ● Theory of Screws: A Study in the Dynamics of a Rigid Body, Robert Stawell Ball, Chapter 1 - Chapter 2
Assignments	● Assignment #4 (4% of Term Assignments) ● Week IV Discussion Topics (2%) ● ROS Programming Examples
Week 5	Statics and Velocity Kinematics
Objectives	● Singularities in Configurations ● The antisymmetric matrix ● Derivation of Rotation Matrices ● The Manipulator Jacobian: Derivation; ● Relating the Spatial to Body Jacobian ● Velocities of the tip and tool frames ● Decoupling singularities ● The principle of virtual work ● Manipulability
Outcomes	●
Readings	● Robot Modeling and Control, Spong, Vidyasagar, and Hutchinson, Chapter 4 ● Modern Robotics, by Kevin Lynch and Frank Park, Chapter 5
Assignments	● Assignment #5 (4% of Term Assignments) ● Week V Discussion Topics (2%)
Week 6	Robot Dynamics and Control
Objectives	● The Euler-Lagrange Equations: Derivation with the *principle of virtual work and Hamilton's principle of least action* ● Applications to Rigid Body Manipulators ● Applications to Semi-rigid manipulators ● Applications to Soft Robotic Applications ● Example implementations for torque control of a mobile robot in ROS ● Holonomic and Nonholonomic Constraints

Outcomes	● Students will demonstrate knowledge about how the mechanical energy of a robotc system constitutes the system's Lagrangian ● Students will then be able to derive the Euler-Lagrange relations for a rigid or semi-rigid mechanical system ● Students will understand the principle of virtual work and virtual displacement ● Deriving the torque for any mechanical system, students will be able to propose and apply control laws to govern the manipulation or motion planning of a robot.
Readings	● Robot Modeling and Control, Spong, Vidyasagar, and Hutchinson, Chapter 5 ● Modern Robotics, by Kevin Lynch and Frank Park, Chapter 8
Assignments	● Assignment #6 (4% of Term Assignments). Students will work with the Navigation stack in ROS 1.x and design a control law for manipulating a mobile robot based on the principles we have studied in class this week. ● Week VI Discussion Topics (2%)
Week 7	Robot Dynamics and Control
Objectives	● Dynamics of a Single Rigid Body ● Twist-Wrench Formulation ● Inverse Dynamics based on Newton-Euler Equations ● Closed-form dynamics equations
Outcomes	● Students will be capable of abstracting the generalized coordinate of any robot ● Given a rigid body, students should be able to establish the forces that influence motion ● For task space control purposes, students will gain a knowledge of constructing the inverse dynamics of the robot
Readings	● Modern Robotics, by Kevin Lynch and Frank Park, Chapter 8
Assignments	● Assignment #7 (4% of Term Assignments).
Week 8	Sampling-based Motion Planning in Robotics
Objectives	● A* algorithm ● Dijskstra's algorithm ● Rapidly Exploring Random Trees (RRTs) ● Probabilistic Roadmap for path planning in high-dimensional configuration spaces
Outcomes	● Students will gain a comprehensive understanding of graph-based and sampling-based motion planning strategies in robot configuration spaces ● Students will be able to come up with specific motion-planning algorithms for their personalized projects
Readings	● Kavraki, Lydia E., Petr Svestka, J-C. Latombe, and Mark H. Overmars. "Probabilistic roadmaps for path planning in high-dimensional configuration spaces." *IEEE transactions on Robotics and Automation* 12, no. 4 (1996): 566-580. ● LaValle, Steven M. "Rapidly-exploring random trees: A new tool for path planning." (1998). ● LaValle, Steven M., and James J. Kuffner Jr. "Randomized kinodynamic planning." *The international journal of robotics research* 20, no. 5 (2001): 378-400.
Assignments	● Assignment #8 (4% of Term Assignments). Students will implement one of RRT or PRM on a mobile robot in a world with obstacles that are personalized for each student.

Week 9	Recent Advancements in Machine-Learning Based Motion-Planning
Objectives	● Introduction to Dynamic Programming ● Random Sampling of States in Robot Navigation ● Differential Dynamic Programming ● Minimax DDP; Minimax Iterative Dynamic Game
Outcomes	● Students will gain a bird's eye-view understanding of dynamic programming ● Students will appreciate the role of optimal control in solving optimization problems ● Students will be able to describe the importance of differential dynamic programming in high-state spaces ● Students will identify when minimax games are important for particular control tasks
Readings	● Bellman, R. (1957). Dynamic programming. *Science (New York, N.Y.)*. Princeton University Press. https://doi.org/10.1126/science.153.3731.34 ● Bellman, R. . Applied Dynamic Programming. ● Fun Reading: Dreyfus, S. (n.d.). RICHARD BELLMAN ON THE BIRTH OF DYNAMIC PROGRAMMING. Retrieved from https://web.archive.org/web/20050110161049/http://www.wu-wien.ac.at/usr/h99c/h9951826/bellman_dynprog.pdf ● Jacobson, David H., and David Q. Mayne. "Differential dynamic programming." (1970).
Assignments	● Students will implement one of iLQG, Minimax DDP or Minimax iDG ona robot of their choice in Gazebo, ROS MoveIt! Motion planner or Mujoco. This will constitute 20% toward the class project of the student.
Week 10	Deep Reinforcement Learning
Objectives	● Reinforcement Learning ● Policy gradients ● Policy Search ● Guided Policy Search
Outcomes	● Students will gain an understanding of the role of deep reinforcement learning in controlling high-dimensional state spaces ● Students will be able to tell the difference between policy gradients and policy search ● Students will understand the inner workings of the guided policy search algorithm
Readings	● Deisenroth, M. P. (2011). A Survey on Policy Search for Robotics. *Foundations and Trends in Robotics*, *2*(1), 1–142. https://doi.org/10.1561/2300000021 ● Levine, S., & Koltun, V. (2013). Guided Policy Search. *Proceedings of the 30th International Conference on Machine Learning*, *28*, 1–9. Retrieved from http://jmlr.org/proceedings/papers/v28/levine13.html ● Sutton, R. S., & Barto, A. G. (2015). Reinforcement Learning : An Introduction, Second edition. ● Levine, S. (2018). Reinforcement Learning and Control as Probabilistic Inference: Tutorial and Review. Retrieved from https://arxiv.org/pdf/1805.00909.pdf
Assignments	● Students will write a term paper that articulates summarizes the state of the art in deep reinforcement learning for robot manipulation as well as describe their disadvantages. This will count as 20% towards Class Project

III. Course Policies and Procedures

Late Policies

- Discussion responses will be accepted up to 3 days late with a 5-point deduction per day.
- Homework assignments will be accepted up to one week late with a 20 percent deduction per day.
- Substantive responses to discussion posts and the final project will NOT be accepted late.

Grading Standards

Work expectations

Students are responsible to explore each week's materials and submit required work by their due dates. On average, a student can expect to spend approximately **12-15 hours per week** completing the readings, activities, and assignments for this course. The calendar of assignments and due dates is located at the end of this syllabus, and all assignments are due by the close of the associated week (Tuesday evenings, 11:55 EST).

100-94	A
93-90	A-
89-87	B+
86-83	B
82-80	B-
79-77	C+

76-73	C
72-70	C-
69-67	D+
66-63	D
62-60	D-
59 or <	F

Feedback

I will provide weekly feedback on your participation.   Your homework and exams will be graded within 1 week of receipt and grades will be posted on LATTE.

Confidentiality

We can draw on the wealth of examples from our organizations in class discussions and in our written work. However, it is imperative that we not share information that is confidential, privileged, or proprietary in nature. We must be mindful of any contracts we have agreed to with our companies. In addition, we should respect our fellow classmates and work under the assumption that what is discussed here (as it pertains to the workings of particular organizations) stays within the confines of the classroom.

Members of the University's technical staff have access to all course sites to aid in course setup and technical troubleshooting. Program Chairs and a small number of Graduate Professional Studies (GPS) staff have access to all GPS courses for oversight purposes. Students enrolled in GPS courses can expect that individuals other than their fellow classmates and the course instructor(s) may visit their course for various purposes. Their intentions are to aid in technical troubleshooting and to ensure that quality course delivery standards are met. Strict confidentiality of student information is maintained.

IV. University & Division of Graduate Professional Studies Standards

Please review the policies and procedures of Graduate Professional Studies, found here: http://www.brandeis.edu/gps/students/studentresources/policiesprocedures/index.html

Accessibility and Accommodations

Brandeis seeks to welcome and include all students. If you are a student who needs accommodations as outlined in an accommodations letter, please communicate with me and present your letter of accommodation as soon as you can. I want to support you.

In order to provide accommodations, I need the letter more than 48 hours in advance. I want to provide your accommodations, but cannot do so retroactively. If you have questions about documenting a disability or requesting accommodations, please contact Student Accessibility Support (SAS) at 781.736.3470 or access@brandeis.edu.

Academic Honesty and Student Integrity

Academic honesty and student integrity are of fundamental importance at Brandeis University and we want students to understand this clearly at the start of the term. As stated in the Brandeis Rights and Responsibilities handbook, “Every member of the University Community is expected to maintain the highest standards of academic honesty. A student shall not receive credit for work that is not the product of the student’s own effort. A student's name on any written exercise constitutes a statement that the work is the result of the student's own thought and study, stated in the students own words, and produced without the assistance of others, except in quotes, footnotes or references with appropriate acknowledgement of the source." In particular, students must be aware that material (including ideas, phrases, sentences, etc.) taken from the Internet and other sources MUST be appropriately cited if quoted, and footnoted in any written work turned in for this, or any, Brandeis class. Also, students will not be allowed to collaborate on work except by the specific permission of the instructor. Failure to cite resources properly may result in a referral being made to the Office of Student Development and Judicial Education. The outcome of this action may involve academic and disciplinary sanctions, which could include (but are not limited to) such penalties as receiving no credit for the assignment in question, receiving no credit for the related course, or suspension or dismissal from the University.

Students may be required to submit work to TurnItIn.com software to verify originality. TurnItIn is a tool that compares student assignment submissions to internet sources and a comprehensive database of other papers. It creates a report that provide a link to possible matches and a '”similarity score”. TurnItIn does not determine whether a paper has been plagiarized; individual faculty will make that judgment. All papers submitted to TurnItIn are kept in a separate reference database of Brandeis work, to be used solely for the purpose of detecting plagiarism in the future. Students retain copyright on their original course work. Allegations of alleged academic dishonesty will be forwarded to the Director of Academic Integrity. Sanctions for academic dishonesty can include failing grades and/or suspension from the university. Citation and research assistance can be found at Library guides

Further information regarding academic integrity may be found in the following publications: "In Pursuit of Excellence - A Guide to Academic Integrity for the Brandeis Community", "(Students') Rights and Responsibilities Handbook", AND " Graduate Professional Studies Student Handbook". You should read these publications, which all can be accessed from the Graduate Professional Studies website. A student that is in doubt about standards of academic honesty (regarding plagiarism, multiple submissions of written work, unacknowledged or unauthorized collaborative effort, false citation or false data) should consult either the course instructor or other staff of the Rabb School Division of Graduate Professional Studies.

University Caveat

The above schedule, content, and procedures in this course are subject to change in the event of extenuating circumstances. If you have questions or concerns about course content before the start of the course, please contact the instructor.