Course: ENPM640 - Rehabilitation Robotics
Semester: Fall 2023 (August 28 – December 19)
Day(s): Monday
Time: 4:00 - 6:40 pm
Location: JMP 2217
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Course Description

This course provides an introduction to a field of robotics dedicated to improving the lives of people with disabilities. The course is designed for graduate students wishing to learn more about the *rehabilitation robotics*, an emerging and one of the fastest growing fields of robotics. Rehabilitation robotics is the application of robots to improve the quality of life for individuals suffering from neurologic injuries and physical trauma. In contrast with other sub-specialties and/or courses in robotics, this course considers not only engineering design and development, but also the human factors that make some innovative technologies successful and others commercial failures. Engineering innovation by itself - without considering other factors such as evidence-based R&D and product acceptance – may mean that some technologies don't become or remain available or are inefficacious to aid their intended beneficiaries. This course differs from medical robotics in its focus on improving the quality of life through robot-mediated *rehabilitation treatments*, rather than improving or enhancing applications such as surgical interventions.

Course Objectives: The course provides the students with an introductory exposure and fundamental understanding of rehabilitation robotics. In particular, it provides the ***theoretical knowledge*** of automatic control systems deployed in rehabilitation robots (position control, force control, impedance/admittance control, series dynamics) and insight into selection of appropriate control system strategy(ies) based on the targeted disability condition and the impairments that result from it. In particular, the course will provide both qualitative and quasi-rigorous perspectives on *impedance control*, the gold standard for human-robot interaction control for many clinically efficacious rehabilitation robots. The course provides information about general considerations underlying different rehabilitation robots taking into account clinical and biomechanical needs of the targeted disabilities. It introduces students to fundamentals of human biomechanics and ***experimental techniques*** used in gait analysis to enable understanding of how such knowledge is necessary to evaluate human movement performance, a key aspect of characterizing the efficacy of rehabilitation robots in clinical settings. Through selected state-of-art literature, selected research and commercial grade rehabilitation robots are introduced to provide students with a basic ***knowledge of the field***. The course will take students through a "virtual" design and development process for at least one example rehabilitation robotic platform to illustrate the ***engineering principles*** and ***hardware selection*** for key robot subsystems (sensors, actuators, motors, and controller) and to facilitate an understanding of how design decisions are made to achieve the subsystem and overall robot performance toward alleviating specific disabilities. This will include conceiving possible changes to the hardware design and/or controller to either improve human performance or motivate the next-generation of the device/s. The course will also introduce students to the ***methodology*** for clinical study design, while presenting some seminal clinical studies/trials utilizing rehabilitation robots, highlighting their study rationale, experimental design, and key findings, as well as ***ethical and regulatory guidelines*** in the field of rehabilitation robotics. At appropriate times during the course, the instructor will bring one or more robots into the classroom for viewing and/or demonstration/s. Finally, one or more expert guest lectures on selected topics such as the biology and epidemiology of neurologic disease (such as stroke) and perspectives/experiences of physical therapists in utilizing rehabilitation robots will uniquely complement the subject matter covered.

ELMS Site or Course Webpage: ENPM640 will be using the CANVAS course environment this semester. Students can login to their course(s) by going to http://elms.umd.edu/page/student-support. A University online identity and password are required to access CANVAS. Information on your University password is available at http://www.it.umd.edu/password/. CANVAS offers many choices for notification about course activities. It is each student's responsibility to set their communication preferences for their Canvas accounts. Information posted on CANVAS will govern course operation. Lectures, readings, videos, announcements etc. will be put on CANVAS.

Required Technology: This is a lecture-based course with no lab, no clickers or software is needed.

Prerequisites: Basic understanding of linear time-invariant control systems (e.g., ENPM667 or equivalent) is highly preferred. No background or previous experience in robotics, biomechanics, and/or neuroscience is required. Students who have previously taken ENME444 "Assistive Robotics" should **not** enroll in this course.

Method for Communication with Students Outside the Classroom: Students may communicate with the Instructor on CANVAS, or by email regarding class cancellation, room change, or other timely announcements. Students may also reserve by appointment, time ahead of class in the OAEE Conference Room, or communicate virtually over Skype/Zoom to discuss course related content, questions, or concerns. Instructor will keep weekly virtual office hours on Fridays between 9 am – 11 am. Office hours will be held via phone and Skype. In-person consultations with the Instructor can be made with prior arrangements.

Statement of Course Goals and List of Student Learning Outcomes

- Identify the parts of the human rehabilitation system (the "**target**").
- Develop understanding of common neurologic injuries such as stroke and their effects on physical function.
- Have a basic understanding of brain neuro-plasticity, motor learning concept, and how rehabilitation robots leverage brain plasticity to restore function (the "**mechanism**").
- Develop a basic understanding of human biomechanics with an emphasis on walking.
- Understand bio-instrumentation techniques to assess human movement performance, diagnose movement disorders, and evaluate rehabilitation outcomes (the "**evaluation**").
- Discuss types of rehabilitation robots, their designs, and their applications (the "**technology**").
- Understand different control systems (position, force, impedance), pros vs. cons, and their suitability for different rehabilitation robotic applications requiring physical human-machine interaction (the "**control**").
- Use engineering principles to identify and address a specific rehabilitation need (disability), design and develop a virtual rehabilitation robot including its hardware and control system, and defend the solution (the "**machine**").
- Develop skills to interpret clinical findings resulting from application of rehabilitation robots in the lab and clinic and virtually design simple clinical trials (the "**clinical study design**").

Course Schedule: The course will be conducted per the following schedule, but is subject to minor changes if certain topics need greater emphasis and detail as the course progresses.

Lecture Topic	**Week**
Robot fundamentals: Characteristics, terminology, mechanical taxonomy, forward/inverse kinematics, multiple or no solution scenarios, eliminating pose/actuator/trajectory redundancies, minimum jerk criterion, Jacobian.	1
Position-regulated control systems: Issues with position control (prelude), the need/benefits of feedback, feedback vs. programmable controller, control law, concept of contact constraints, transient response with/without programmable feedback controller, critical damping.	2
Position-regulated control systems: *(Part I)* Frequency domain modeling, performance metrics, steady-state error (SSE), error regulation, effect of constant gain on SSE, stability types & poles, SSE vs. stability tradeoff, improving transient response/SSE through position-regulated control. *(Part II)* Control law partioning, trajectory-following/direct error control, prelude to interaction control.	3
Fundamentals of Interaction Control: *(Part I)* Mechanical impedance/admittance, qualitative underlying principles of impedance control (IC), interactive relationships to deficit severity, key questions in IC, biological inspirations. *(Part II)* Isolated vs. contact stability with position & force feedback, practical problems associated with contact instability, drawbacks of disturbance rejection & uncertainty modeling approaches, interaction port, formal definitions of impedance/admittance for linear & non-linear systems, IC as a solutuion to contact instability, port impedance/admittance vs. transfer functions.	4
Analysis of Coupled Systems: *(Part I)* Bond graphs, causality, impedance/admittance reduction, choice for impedance/admittance (preference vs. requirement), Nyquist stability. *(Part II)* Passive systems, stability vs. passivity, coupled system stability analysis, practical tests for passivity, static impedance control.	5
Impedance/Admittance Controllers: *(Part I):* Hierarchy of stability types (nominal/coupled/command following), generalized interactive dynamics transfer function, simple impedance control (SIC), pros vs. cons of SIC. (Part II) Force feedback, pros vs. cons of pure force feedback, physical equivalent systems, natural admittance control (NAC), series dynamics.	6
Rehabilitation and Biomechanics: Perspectives/definitions, assistive vs. therapeutic robots, measurement of human walking, gait analysis, gait cycle/phases/events, spatial/temporal gait, walking disorders in stroke.	7

Lower Extremity Rehabilitation Robotics: Need for neuro-rehabilitation, end-effector vs. exoskeletal robots, paradigm shifts (brain science/rehabilitation/technology), modularity, back-drivability, limitations of conventional gait therapy, "though experiment(s)".	8
Design of Lower Extremity Robot: Product lifecycle (concept—prototyping—bench trials—preclinical trials—clinical trials), detailed example to illustrate hardware selection & controller design.	9
Ankle Robotics for Lower Limb Rehabilitation: Clinical needs, concept of under-actuation, the Anklebot as an example motor learning robotic platform (design/component selection/bench validation/estimating position using models/estimating stiction/impedance characterization).	10
Clinical Impact of Ankle Robotics: *(Part I)* Videogame-based Anklebot training in chronic and sub-acute stroke. *(Part II)* Anklebot gait therapy including challenges and solutions for stabilizing interaction during robot-assisted walking; key clinical findings to determine rehabilitation efficacy.	10
Future Directions for Lower Limb Robotics: Different disease conditions/mobility activities, untethering devices, pediatric applications, TRIZ design principle, MIT-Sky Walker.	11
Clinical Study Design & Guidelines Types of studies in rehabilitation robotics (interventional/observational, parallel group/dose-ranging/cross-over), role of health economics: VA-COOP Trial, study design process (randomization, stratification, blinding), ethical and regulatory guidelines.	12-14

Exams: Mid-term and final exams will be takehome. Solutions are to be returned by email.

Due Dates: Assignments will be assigned as per the following schedule.

Grading Event	**Topic(s)**	**Assigned**	**Due**
Homework 1	Fundamentals of robots, position control systems.	End Week 3	End Week 4
Homework 2	Impedance control, gait biomechanics.	End Week 5	End Week 6
Midterm Exam	Robot fundamentals, position & impedance control, gait biomechanics, LE (ankle) robots.	End Week 8	End Week 9
Project	Design of rehabilitative robotics	End Week 7	Reading Day
Final Exam	All materials	Finals Week	

Expectation for Students: Students are expected to fully participate in the course by attending all lectures (unless excused by the instructor in writing – see Attendance/Participation Policy), turn in their homeworks on time (see Grading Procedures), and be as interactive as possible in the lectures in terms of Q&A. These are toward supporting a successful student experience in the context of the course.

Grading Procedures: Two homework assignments (10% each, total 20%), Mid-term exam (15%), Final exam (25%), and Project (40%). Final grade distribution will be *A+* = 96-100, *A* = 90-95, *B+* = 85-89, *B* = 80-85, *C+* = 75-79, *C* = 70-74, *D+* = 65-69, *D* = 60-64.

Note on Late Assignments: Assignments that are submitted between 1 minute and 24 hours late will receive 75% of the credit. Assignments that are more than 24 hours late will receive 0% of the credit. Exceptions will be made in accordance with University policy regarding these major grading events.

Course Attendance/Participation Policy: Regular attendance at lectures is expected and 5% of the total grade is based on attendance. Students are responsible for inquiring about and obtaining course material delivered in their absence (from course colleagues). University policy excuses the absences of students for illness (self or dependent), religious observances (see Policy Here), participation in University activities at the request of University authorities, and compelling circumstances beyond the student's control. Students must submit the request in writing and supply appropriate documentation, e.g. medical documentation. Students with written, excused absences are entitled to a makeup exam (or assignments if applicable) at a time mutually convenient for the instructor and student. For more information, see UMD's policy on medically necessitated absences from class.

Written Absence Policy: Students must submit the request in writing and supply appropriate documentation, e.g. medical documentation. Students with written, excused absences are entitled to a makeup exam (or assignments if applicable) at a time mutually convenient for the instructor and student. For more information, see UMD's policy on medically necessitated absences from class.

Arrangements for Students with Disabilities: UMD is legally obligated to provide appropriate accommodations for students with disabilities. The campus's **Disability Support Service Office** (DSS) works with students and faculty to address a variety of issues ranging from test anxiety to physical and psychological disabilities. If an instructor believes that a student may have a disability, DSS should be consulted (4-7682 or **dissup@umd.edu**). Note that to receive accommodations, students must first have their disabilities documented by DSS. The office then prepares an Accommodation Letter for course instructors regarding needed accommodations. Students are responsible for presenting this letter to their instructors by the end of the drop/add period.

Copyright Notice: Course materials that exist in a tangible medium, such as written or recorded lectures, Power Point presentations, handouts and tests, are copyright protected. Students may not copy and distribute such materials except for personal use and with the instructor's permission. Course materials may also be marked copyrighted (e.g. ©2016 Roy).

Textbook(s)

There is **no required textbook** for this course. Teaching materials include instructor's lecture slides and notes, and reading materials (selected journal and scientific conference proceeding articles). These will be posted on CANVAS at appropriate times (typically, lecture slides are posted on CANVAS after each lecture).

Course Outline

The course content will be delivered sequentially in two parts: first, an understanding of feedback control systems, both position-regulated control (to foster understanding of trajectory-following rehabilitation robots) and interaction control (to foster understanding of impedance-controlled rehabilitation robots), followed by introductory concepts on human biomechanics and rehabilitation; and second, detailed exposure to rehabilitation robotics. As rehabilitation robotics is a very broad sub-specialty by itself, robotics for restoration of lower-limb function will be used as an example model throughout; however, both students will be exposed to upper-extremity (arm) robotics.

- Control Systems: frequency domain modeling/analysis, mechanical transfer functions, response of first and second-order systems and performance metrics, error regulation, stability analysis, improving transient response/error regulation through P, PI, and PID controllers, control law partioning, and trajectory-following control of position-regulated control systems; fundamental concepts of impedance/admittance control, qualitative examples, compliance mirroring, isolated/contact stability, drawbacks of disturbance rejection/uncertainty modeling approach, interaction port, impedance/admittance, causal analysis, guidelines for appropriate choice for impedance/admittance, coupled system stability analysis, advanced interaction control (simple impedance control, force feedback, natural admittance control, series dynamics).

- Rehabilitation: Definition and different perspectives; parts of the human rehabilitation system; types of functional impairments due to neurologic injuries; concept of neuro-plasticity; principles and models underlying motor learning (massed-practice, feedback, goal setting); gait biomechanics; types of walking disorders: and types of bio-instrumentation and techniques (measurement-analysis) of gait and balance functions.

- Robotics: Terminology and taxonomy (operating principle, population targeted etc.), interesting and unique challenges of blending and interaction control of robotic (precise system) with frail populations (uncertain system); concept and benefits of under-actuation; different engineering subsystems in rehabilitation robotics (sensors, controllers, actuators); pros and cons of different designs and operating principles in various rehabilitation research and commercial grade robots; different controllers (position, impedance) and their pros and cons; considerations for choice of appropriate control system and robot hardware; solutions for stabilizing interaction during complex tasks such as robot-assisted walking; latest clinical findings and their interpretations regarding rehabilitation efficacy of robots commonly deployed in the clinic and research labs (clinical trials); and ethical guidelines for human subjects testing including clinical trials with rehabilitation robotics.

Code of Academic Integrity

The University of Maryland, College Park has a nationally recognized Code of Academic Integrity, administered by the Student Honor Council. This Code sets standards for academic integrity at Maryland for all undergraduate and graduate students. As a student you are responsible for upholding these standards for this course. It is very important for you to be aware of the consequences of cheating on exams, cheating on clicker quizzes in lecture, fabrication, facilitation, and plagiarism. For more information on the Code of Academic Integrity of the Student Honor Council, please visit http://shc.umd.edu/SHC/PledgeInformation.aspx.