EE 628

Force Control and Bilateral Teleoperation

Fall 2020

Course Information

Time:	Tuesday 3:40pm – 5:30pm and Wednesday 11:40am – 12:30pm
Credit:	3 credit hours
Tuesday	`https://sabanciuniv.zoom.us/j/93133323879?pwd=eGlEaTZpWENGV2l3YmVodGhuOHdNUT09`
Wednesday	`https://sabanciuniv.zoom.us/j/93150692000?pwd=NW5hbnF1SzFCeTQ3WFlKUUVnNml5dz09`

Instructor

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Resources

Web Site:	Available through SUCourse+.
Recommended Reading:	Research papers, book chapters, and supplementary material will be assigned throughout the term.

Prerequisites

Students are expected to have a working knowledge of differential equations, linear systems and strong background in feedback control systems. Familiarity with programming, especially with C and Matlab/Simulink is also required. Course involves hands-on laboratory components. Furthermore, **instructor's approval is required to register for this advanced graduate course**.

Purpose

This course is designed to equip students with fundamental theories and computational methodologies that are used in (computer aided) analysis and synthesis of force controlled and bilaterally tele-operated systems. By the end of the course a solid understanding of the principles of force/bilateral control in the context of modern classical control and hands-on experience with implementation of force/bilateral controllers on modern force feedback devices are aimed. The course is appropriate for students in any engineering discipline with interests in robotics, nonlinear controls, and haptics.

After a short review of classical/modern control techniques and fundamental limitations of feedback control, students will be introduced to the challenges of explicit force control. Alternatives to explicit force control, such as series elastic actuation, impedance control, and admittance control will be studied. Concepts of passivity and positive realness will be introduced and rigourously applied to coupled stability analysis of interaction controllers. Passivity based control techniques, such as Passive Velocity Field Control will be introduced. Fundamentals of virtual environment simulation and haptic rendering will be covered, emphasizing the destabilizing effects of energy leaks introduced due to sampled data effects. Passivity of the human-in-the-loop sampled data system will be analysed. Robust stability and transparency of general [scaled] teleoperation architecture (4-channel with local force feedback) will be studied and the trade-off between these two competing criteria will be demonstrated. Finally, time permitting, communication/computation delays will be introduced and two approaches to compensate for the time delay, namely, time domain passivity and wave variables, will be illustrated.

The emphasis of this course is not only on rigorous mathematical analysis, but also an integrated understanding of mechanical design, physical modeling, stability analysis, controller synthesis, and hardware-in-the-loop implementation of force/bilateral control systems. Special attention is paid to the decisions made in the mechanical design process, since closed loop performance of the overall system is directly affected, and in many cases limited, by the physical characteristics of the plant. An intuitive understanding of major nonlinear system analysis tools, such as frequency domain passivity, is sought, since a solid understanding of concepts help students better appreciate the reasoning behind physical system modeling and controller synthesis. Real-time hardware-in-the-loop implementation of the controllers is also emphasized such that students can experience the control challenges of the real world, such as sensor noise and unmodeled system dynamics.

Application areas of force feedback devices (haptic interfaces) and bilateral teleoperators include (but are not limited to) robotic devices for physical rehabilitation, active exoskeletons and prostheses for human augmentation, force-feedback devices for robot-assisted surgery, haptic interfaces for manual skill training, teleoperators for exploration of hazardous or remote environments, x-by-wire systems for automotive/aerospace industry, and service robots for collaborative task execution with humans.

Course Objectives

The goal of this course is to equip each student with an integrated understanding of fundamental theories and computational methodologies that are used in (computer aided) analysis and synthesis of force controlled and bilaterally teleoperated systems. By the end of the course, each student should be able to do the following:

1. Derive sensitivity and complementary sensitivity functions of MIMO LTI systems and explain fundamental limitations of feedback control.
2. Check for internal stability of MIMO LTI systems.
3. Identify the differences between BIBO stability, Lyapunov stability, passivity, and unconditional stability.
4. List the major challenges in explicit force control and analytically demonstrate major reasons for chatter.
5. Synthesize and implement explicit force controllers with guaranteed coupled stability.
6. Synthesize and implement impedance/admittance controllers with and without force feedback.
7. Compare several force control architectures, discuss the mechanical properties of the plant favored by each controller, and select the appropriate controller for any given plant.
8. Construct and formulate physics based simulations of virtual environments.
9. List the sources of energy leaks in haptics rendering and discuss the compensation approaches.
10. Implement passive haptics renderings of physics based simulation of virtual environments.
11. Compute equivalent inertia/damping/stiffness of an impedance transfer function and discuss rendering fidelity.
12. Construct the 4-channel bilateral teleoperator architectures with local force feedback and demonstrate the fundamental trade-off between stability and transparency.
13. Compare different architectures for bilateral teleoperation and discuss their advantages/disadvantages.
14. Design and implement passivity based controllers for stable [scaled] teleoperator architectures.
15. Demonstrate destabilizing effects of time delay and discuss approaches to compensate for these effects.

Homework Sets

Homework sets and implementation tasks will be assigned regularly and posted on the course website.

Exams

There will be one (possibly take home) mid-term and one (possibly take home including a presentation) final exam. Since the course continually builds upon previous material, all exams will be comprehensive. All exams are closed book and notes, with one page of personally prepared notes. By registering to this course, students consent that they will secure a reliable internet connection, a camera and a audio recorder and will follow the detailed instructions to be provided for the online exams.

Lecture

The lecture format will be loose. There may be a short break during the two hour lecture period. Lectures will involve student presentations, discussion and laboratory activities. Extra lectures, laboratory and problem solving sessions may be scheduled as necessary. Class participation and cooperation among students are highly encouraged. Student feedback will be collected throughout the semester and adaptation will be undertaken accordingly.

Project

Students will be given the freedom to choose a project topic of their interest, subject to instructor's approval. A list of possible project topics will also be recommended by the instructor. A candidate project topic should address a real life problem (preferably related to an open research problem) and should involve sufficiently complex analysis to let students demonstrate their proficiency at a technical level. All project reports need to be prepared in LaTeX and should be presented to the class.

Grading Policy

The course grades are determined from the total points students receive from homework sets, laboratory assignments, midterm and final exams, project, and class participation.

Homework sets and project must be submitted to SUCourse+ by the deadline. No late problem sets are accepted. (Extensions may be granted for special circumstances and only when requested at least one day in advance.)

Students are responsible for all information given in class verbally and/or in writing. Any information about the course on the web may be replaced by the information given in class.

Cooperative efforts at understanding the course material and the assignments are encouraged. However, each student may only submit work that he/she has completed individually. For example, students may communicate verbally about methods for solving assigned problems, but sharing of written work is not permitted. Submitting any work that is not the result of a student's own effort is considered cheating and subject to disciplinary action.

Assignments:	20%
Midterm Exam:	25%
Project:	20%
Final Exam:	25%
Participation:	10%
	100%

Other Notes

Any student with a disability requiring accommodation in this course is encouraged to contact the instructor during the first two weeks of the semester.

Additional Reading

Research papers, book chapters, and supplementary material will be assigned throughout the term.

Tentative Schedule and Topics

Weeks 1 – 2	*Review of Fundamental Concepts from Classical and Modern Control* Linearization: Small Signal and Feedback Linearization Frequency Response, Vector Margin Input/Output and Internal Stability Sensitivity and Complementary Sensitivity Functions Stability Robustness and Sensitivity to Parameter Variations Fundamental Trade-off of Feedback Control Pre-compensation and Two Degree of Freedom Control Setpoint and Trajectory Tracking MIMO Systems: Stability Robustness
Weeks 3 – 7	*Interaction Control* Explicit Force Control Fundamental Limitations of Explicit Force Control Series Elastic Actuation Coupled Stability, Complementary Stability and Passivity Implicit Force Control Methodologies Impedance and Admittance Control Architectures Macro-Micro Actuation Disturbance/Force Observers
Weeks 8 – 10	*Haptic Rendering* Virtual Environments Collision Detection Dynamic Simulation Interaction Force Generation Penalty-based Haptic Rendering Performance Criteria and Fidelity of Haptic Rendering Discrete Time Effects: Sampling, ZOH, Quantization Passivity of Virtual Environments: Network Theory and Energy Leaks Modeling Human Operator: Passivity Assumption and Crossover Model
Weeks 11 – 14	*Bilateral Teleoperation* Teleoperator Architectures Four-Channel Teleoperator Architecture with Local Force Feedback Transparency and Kinesthetic Coupling Robust Stability vs Transparency Tradeoff Impedance Shaping and Scaling in Bilateral Teleoperation Time Domain Passivity: Passivity Observer/Passivity Controller Scattering Theory and Wave Variables