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Topics: Haptic technology

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Physical Student-Robot Interaction with the ETHZ Haptic Paddle

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sequences and the oral exam were explicitly aligned to these learning objectives. The outcomes of the specialization project presentations and oral exams, and a student evaluation of the course, demonstrated that the ETHZ haptic paddle is a valuable tool that allows students to quite literally grasp abstract principles such as mechanical impedance, passivity and human factors, and helps students create a tangible link between theory and practice in the highly interdisciplinary field of pHRI.

Index Terms—Dynamic systems, hands-on laboratory, haptics, human factors, performance metrics, physical human-robot interaction (pHRI), psychophysics, specialization projects.

I. INTRODUCTION

Physical human-robot interaction (pHRI) is an interdisciplinary research field that has grown rapidly and attracted increasing interest over the past decade; its applications are in biomedical, assistive and rehabilitative robotics as well as in haptics/motor control research and consumer platforms [1-6]. To understand and apply correctly the key concepts of pHRI, engineering students must connect the knowledge they have acquired in their previous physics, mechanics, dynamic systems and controls classes, link this novel fields such as haptics, human factors, psychophysics, and familiarize themselves with the many practical boundary conditions involved.

Hands-on experience plays a crucial role in strengthening the understanding of basic engineering concepts [7, 8]. Many of these concepts can only be learned through personal experience, and cannot be transmitted through classroom lectures alone [9]. Currently, only a few practical sessions are offered in the Mechanical Engineering Bachelor's curriculum at ETH Zurich, including an inverted pendulum in the Digital Control Systems course [10], a haptic wheel in the Embedded Controls course [11] and a two degree-of-freedom (DOF) manipulator in the Introduction to Mechatronics course [12]. Compounding the problem is the fact that practical laboratory courses can only accommodate a limited number of students, while the enrollment in Mechanical Engineering has risen considerably over the past years (to 446 students in 2011).

Haptic paddles have been used with great success at several universities in the United States to teach lectures on dynamic systems, haptics and pHRI [13-15] (for an overview refer to [16]). A haptic paddle is a simple, one degree-of-freedom device under computer control, capable of rendering virtual dynamics while interacting with the human hand. As Blake Hannaford, a professor at the University of Washington and one of the pioneers in haptics and pHRI, aptly summarized during a workshop on Best Practices for Teaching Haptics at the 20th anniversary 2012 Haptics Symposium [17]: "The haptic paddle is transparent in multiple ways". This statement refers to *i)* the simple design, making the functioning principle intuitively accessible to any engineering student, *ii)* the low inherent output impedance of the setup, resulting in a highly transparent device that accurately renders the controlled dynamics, and *iii)* the see-through acrylic design adopted in many versions of the haptic paddle.

Motivated by the many positive experiences documented using haptic paddles at other universities as well as by the potential of such enhanced pedagogical learning, the

ETHZ haptic paddle was developed. The paddle was introduced as a hands-on teaching device in a new undergraduate course on pHRI, targeting upperclassmen engineering students in the Mechatronics Focus track of the Mechanical Engineering curriculum at ETH Zurich [18]. The ETHZ haptic paddle is a further development of the haptic paddle developed at Rice University [19], introducing some novel features such as a USB data acquisition card and a custom-designed linear current amplifier. A series of hardware additions, including a force sensor, optical encoder or tachometer, are provided later in the semester for the purpose of specialization projects allowing pairs of students to investigate advanced topics in pHRI. The aim was for students to have direct physical experience of concepts such as mechanical impedance [20], stability and human factors, to highlight the interdisciplinary approach required for assistive and rehabilitative robotic systems, and to improve their teamwork and presentation skills through the group project and a technical talk.

This novel course allows students to i) learn by doing, ii) grasp (literally) theoretical concepts by applying them to the haptic paddle, and iii) familiarize themselves with standard data acquisition hardware and visual programing software that they are likely to encounter again during their subsequent research projects, or later in their academic or industrial career. Furthermore, students enjoy the projects with the haptic paddle, and this strong motivational emotional component is thought to support the cognitive learning process [21]. The authors hypothesized that this unique combination would help students to integrate and associate the concepts from individual disciplines and to establish stronger links between theory and practical experience, resulting in improved learning with increased depth and structure of knowledge. The effect of this approach on the observed learning outcomes was assessed through the final presentations and oral exams, according to the principles of the Structure of Observed Learning Outcomes (SOLO) taxonomy [22], using Bloom's revised taxonomy [23] as a marker.

II. Materials and Methods

A. Learning Goal and Specific Learning Objectives

The learning objectives of this course were formulated in the context of a faculty development program offered to ETH Zurich assistant professors by the Educational Development and Technology Center. The overall goal of the course was defined as:

> *Students should understand the critical elements in human-robot interactions — both in terms of engineering and human factors — and use these to evaluate and design safe and efficient assistive and rehabilitative robotic systems.*

The detailed learning objectives divided this overall goal into the major design and evaluation steps (driven by interdisciplinary requirements) involved in creating a new human-interactive robotic system. Specifically, at the end of the course, students should be able to:

1) Identify critical human factors in physical human-robot interaction and use these to derive design requirements
2) Compare and select mechatronic components that optimally fulfill the defined design requirements

3) Derive a model of the device dynamics to guide and optimize the selection and integration of selected components into a functional system
4) Design control hardware and software, and implement and test human-interactive control strategies on the physical setup
5) Characterize and optimize such systems using both engineering and psychophysical evaluation metrics
6) Investigate and optimize one aspect of the physical setup, and convey and defend the gained insights in a technical presentation

B. Course Overview

The pHRI course introduced in the autumn semester of 2011 comprises a two-hour lecture and a two-hour hands-on laboratory session each week for fourteen weeks. The enrollment was limited to twenty students, a constraint imposed by the ten hardware setups available in this first phase. The lecture syllabus is given in Table and on the lecture website [24].

To give the students an overview of the applications and challenges in the field of pHRI, a representative of Force Dimension [25] gave a guest lecture in the first week, followed by demonstrations during the first hands-on laboratory session. The demonstrations included *i)* CHAI3D renderings [26] on an omega.3 haptic display (Force Dimension, Nyon, Switzerland), *ii)* the haptic conductor [27], in which the user learns to conduct a music piece by physically experiencing the gestures of a professional conductor, via a Phantom Omni [28] haptic display, while watching audiovisual media, *iii)* the Virtual Peg Insertion Test, a robot-assisted assessment of upper limb function in stroke patients as a research application [29] as well as *iv)* the rendering of spheres with different surface properties on the Novint Falcon [6] haptic display.

TABLE I

OVERVIEW OF THE PHRI COURSE, SHOWING THE 14 X 2HR LECTURE SESSIONS, THE 14 X 2HR ETHZ HAPTIC PADDLE LABORATORY SESSIONS, AND THE WEEKLY ASSIGNMENTS.

Week	Lecture (2h)	Laboratory session (2h)	Assignment
1	Introduction and guest lecture	Application examples and demos	
2	Human factors	Explore haptic illusions	Questionnaire
3	Sensing	Introduction to visual programing	LabView tutorial
4	Data acquisition and real-time signal processing	***Part 1*** - signal acquisition	MATLAB plots - raw/filtered position, velocity, acceleration
5	Actuation and motor control in pHRI	- filter design - output control (motor current)	- sensor characterization - voltage/current, current/torque
6	Kinematics, transmission, sensor colocation	Visit to the Rehabilitation Engineering Lab	
7	Basic modeling and electromechanical analogy	***Part 2*** - modeling in MATLAB/Simulink	MATLAB plots - step/ramp/sinusoidal response
8	Basic control	- PID controller	- simulated vs plant response
9	Advanced modeling (friction identification and modeling)	***Part 3*** - system identification (friction)	MATLAB plots - friction/velocity
10	Advanced control (rendering of rigid contact)	- model-based feedforward - spring/damper model, virtual wall	- friction model parameter estimation - step response with feedforward, K-B plot [30]
11	Safety analysis and methods to minimize risk and injury	***Part 4*** Specialization projects (Tab.II)	
12	Application in rehabilitation and assistive technology		
13	Performance metrics	(Prepare presentation)	
14	Student presentation	Specialization projects demos	Data, plots/figures and slides

In the laboratory session following the second lecture on human factors, students could explore a series of haptic illusions (inspired by [31]), including the comb illusion [31], size-weight illusion [32], funneling illusion [33] and the rubber hand illusion [34]. These illusions were presented to make students aware of perceptual limitations of their body, and that providing sensory feedback, e.g., to a prosthesis wearer, is a non-trivial problem.

Some lectures later in the semester were given by Ph.D. students and postdoctoral fellows of the Rehabilitation Engineering Lab, to allow them to practice their communication skills and impart their specific research experience, and to allow undergraduates to interact with lab members.

From the third week onwards, the laboratory sessions used the ETHZ haptic paddle to apply the theoretical concepts learned in the lecture. This section of the course was divided into three two-week parts, followed by a fourth four-week part dedicated to the specialization projects (Section II.D). An assignment was set for each of these parts, which had to be handed in within a week after the last laboratory session of that part. Following a general introduction to visual programming with LabView (National Instruments, Austin, TX, U.S.A.), Part 1 was dedicated to data acquisition, signal processing and motor control, Part 2 to modeling and PID control, and Part 3 to system identification, feedforward gravity and friction compensation, impedance control and performance evaluation, Table I. A visit to the Rehabilitation Engineering Laboratory after Part 1 illustrated research applications of pHRI in motor learning, rehabilitation and assistive technology.

C. ETHZ Haptic Paddle

The ETHZ haptic paddle, Fig. 1, is based on Rice University's haptic paddle [19]. It was adapted to the metric system, and introduces some novel hardware components and features, including a commercial USB data acquisition card for measurement and control, a current amplifier, and a force sensor that students are likely to encounter throughout their academic or industrial career. The paddle has a single rotational degree of freedom actuated via a 15:1 capstan transmission. It's position is measured via a Hall effect sensor (Continuous-Time Ratiometric Linear Hall Effect Sensor A1301, Allegro MicroSystems, Inc., Worcester, MA, U.S.A.) located on the axis of the paddle, at the end of which a rapid prototype sleeve holding a magnet has been fixed. The ETHZ haptic paddle is actuated by a brushed DC torque motor (20 W, nominal torque 32.3 mNm, type RE 25 339156, Maxon Motor AG, Sachseln, Switzerland) and driven by a custom-designed linear current amplifier with a maximum current of 2 A. For position measurement and motor control, a commercially-available low-cost USB data acquisition card (USB 6008, National Instruments, Austin, TX, U.S.A.) is used, allowing visual programming, accessible to students with limited programing experience (200 Hz control loop in LabView, National Instruments, Austin, TX, U.S.A.). This solution was chosen, rather than an integrated USB controller, as students are likely to meet such hardware throughout their academic and industrial career, and will thus be more easily able to transfer the knowledge acquired in this lecture to the application at hand.

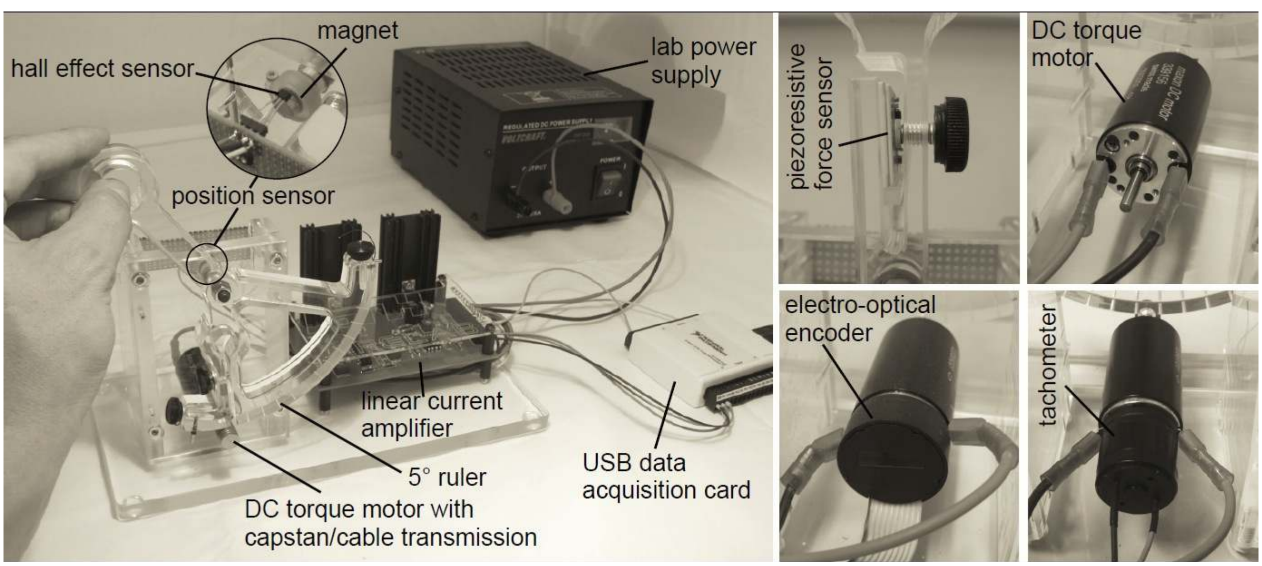

Fig. 1. ETHZ haptic paddle (left) and hardware variations (right). At the beginning of the lecture, all pairs have the same hardware setup, some of which were then expanded (force sensor,

electro-optical encoder, tachometer) for the specialization project during the last four weeks of the semester.

The hands-on laboratories were carried out in a computer room equipped with 20 desktop PCs (Dell, Austin, TX, U.S.A.) running a Windows 7 operating system; the paddles were powered by a regulated laboratory power supply (Voltcraft 24 V/3 A, Conrad Electronic, Hirschau, Germany). While a laptop power supply would also have been a viable option, the lab power supply again confronts students with hardware they will typically use during their research projects.

Linear Current Amplifier: One of the novelties of the ETHZ haptic paddle is the inclusion of a custom-made linear current amplifier, which gives students further insights into the control and behavior of the haptic paddle. The board is equipped with a precision shunt resistor that can be read out with the USB data acquisition card to measure the current flowing through the motor. In the lecture, the transfer function of the analog current amplifier is derived (see also Fig. 2) as follows:

$$I_{mot}(s) = -\left(\frac{V_{in}(s)}{R_1} + \frac{V_0}{R_2}\right)\left(\frac{sR_3C(R_4+R_5)+R_4+R_5}{LC(R_4+R_5)s^2+C(R_LR_4+R_LR_5+R_4R_5+R_5R_3)s+R_5}\right) \quad (1)$$

with static gain:

$$i_{mot} = -\left(\frac{V_{in}}{R_1} + \frac{V_0}{R_2}\right)\left(\frac{R_4+R_5}{R_5}\right) \quad (2)$$

Where V_{in} is the control signal input and V_o the reference input. For the implementation, the following values were used: R_1= 4.7 kΩ, R_2= 4.7 kΩ, R_3 = 2.2 kΩ, R_4= 1 kΩ, R_5 = 0.5 Ω, C = 100 nF. The motor terminal resistance and inductance are taken from the data sheet as R_L = 10.6 Ω, L = 1.25 mH. As the analog output (connected to V_{in}) of the employed data acquisition card (NI USB 6008) is limited to [0, 5] V, the 2.5 V reference output is inverted and connected to V_o to offset the analog output to [-2.5, 2.5] V, and the motor current becomes

$$i_{mot} = -0.43 \cdot (V_{in} - 2.5)[A] \tag{3}$$

with a controllable motor current of [-1.075, 1.075] A.

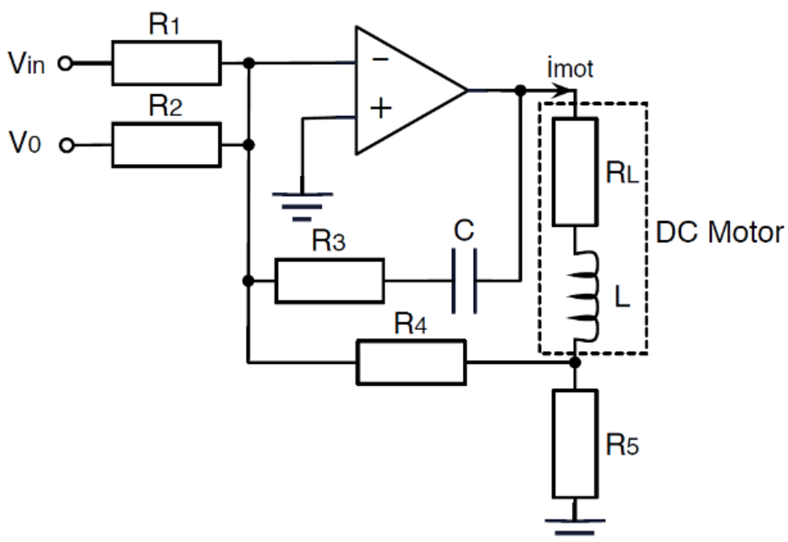

Fig. 2. Schematic of the linear current amplifier for the derivation of the transfer function, adapted from [35].

D. Specialization Projects

In the first week of the lecture, students were provided with a list of 13 specialization projects (Table II) and given access to a virtual learning environment (Moodle, Perth, Australia) containing a detailed description of each specialization project, background literature, expected outcomes and the contact information of the teaching assistant supervising that particular experiment (available online [24]). Student pairs were asked to select within the following week, via a prepared Doodle list [36] and on a first-come, first-served basis, a specialization project of interest to them. They then had several weeks to read through the provided literature and to discuss with the teaching assistants. Two pairs merged for the teleoperation project. To allow for a wider range of advanced topics for the students to delve into, additional hardware was provided to individualize the setups, as listed in Table II and illustrated in Fig. 1.

TABLE II

SPECIALIZATION PROJECTS FROM WHICH PAIRS OF STUDENTS COULD SELECT ON A FIRST-COME, FIRST-SERVED BASIS.

	Specialization Project	Hardware Variations
1)	Effect of quantization and discretization on virtual wall rendering	optical encoder on motor shaft[1] and PCI DAQ card[2]
2)	Velocity measurement	tachometer[3] on motor shaft
3)	Velocity estimation from hall sensor using Levant's differentiator [37] and discrete-time adaptive windowing [38]	
4)	Haptic/VR needle insertion simulation with multiple tissue layers	
5)	Teleoperation between two haptic paddles (2 groups)	PCI DAQ card[2]
6)	Impedance control with force feedback	force sensor integrated in paddle[4]
7)	Admittance control	force sensor integrated in paddle[4], tachometer on motor shaft[3] and linear power amplifier in velocity mode[5]
8)	Identification of output impedance	force sensor integrated in paddle[4]
9)	Electromyographic (EMG) control	custom EMG amplifier and electrodes[6]
10)	Psychophysical study to determine human perception thresholds	
11)	Identification of finger impedance	force sensor integrated in paddle[4]

[1]1000 CPT MR encoder, Maxon Motor AG, Sachseln, Switzerland; [2]NI PCIe-6321, National Instruments, Austin, TX, U.S.A; [3]DC-Tacho DCT 22, 0.52 Volt, Maxon Motor AG, Sachseln, Switzerland; [4]Cento Newton 40N, EPFL-LPM, Lausanne, Switzerland; [5]LSC 30/2, Maxon Motor AG, Sachseln, Switzerland; [6]Blue Sensor N, Ambu, Copenhagen, Denmark.

The laboratory sessions during the last four weeks of the semester were dedicated to the specialization projects. Students were also given access to the hardware and computer room outside of the supervised instruction time, allowing them to continue working on their specialization projects outside the official laboratory sessions. Students were asked to summarize and discuss their main findings and present them to their peers in the final lecture of the semester.

E. Assessment

1) *Alignment:* The aim of the lecture was to guide students through the five design steps summarized by the learning objectives in Section II-A, to teach them the entire process of designing and evaluating a robotic system capable of safely interacting with or supporting human motion, and to allow them to apply this knowledge through the hands-on tutorials. The learning objectives also served explicitly as the basis for interactive sequences during the lectures and for questions in the oral exam (according to the principles of "constructive alignment" [22]).

2) Specialization Project Presentation and Demonstration: In the last lecture, students presented the results and conclusions of their specialization projects to their peers in a 12-minute presentation followed by five minutes of questions and discussion. In the laboratory session directly following the presentations, students demonstrated their specialization setups to the instructors and to their classmates. The presentations and demonstrations were assessed by the authors based on i) the creativity and scientific soundness of the selected approach, ii) the results obtained, iii) the structure and clarity of the presentation and iv) the answers to questions by the authors and their fellow students. This assessment accounted for 25 % of the final grade, but only if this improved upon their exam grade.

3) *Oral Exam:* Exam questions were explicitly based upon the first five learning objectives, and required students to combine and apply knowledge from different domains. Students were assessed on whether they understood the overall design and evaluation process, could elaborate on specific aspects thereof, and apply this in case studies. Two weeks prior to the oral exam, students received a list of 28 topics/questions to use in preparing for the oral exam. The 28 questions were divided into three groups

based on the level of cognitive process they tested: i) remembering/understanding, ii) applying/analyzing and iii) evaluating/creating (see also [23]). In the exam, students were asked one question (drawn randomly) from each group. The exam lasted 25 minutes per student, and was carried out in the last week of the semester, in the same week as the specialization project presentations and demonstrations.

III. RESULTS

By the end of the third laboratory part (week 10, Table I), students successfully implemented an impedance controller (virtual wall) with model feedforward, with the model accounting for gravity as well as Coulomb and viscous friction components. The virtual wall was evaluated through a K-B plot [30], which is related to the Z-width of the device (as discussed below). The parameters of the friction model were identified experimentally from a step response and a friction torque/velocity plot and verified by comparing the behavior (output motion in response to a sinusoidal input current at different frequencies) of the real plant to that of the MATLAB/Simulink (MathWorks, Natick, MA, U.S.A.) model.

A. Impedance Control with Force Feedback and Admittance Control

One of the main novelties of the setup developed was the integration of a low-cost piezoresistive force sensor (CentoNewton, EPFL, Lausanne, Switzerland) in the handle of the haptic paddle, close to the mechanical output. The sensor was used in several of the specialization projects in Table II. The dynamic output range of the device with respect to the output impedance of the uncontrolled device was assessed via an impedance-width (Z-width) plot, Fig. 3, [39], [40], for two types of controllers:

i) impedance control with force feedback and *ii)* admittance control. For the impedance controller, adding force feedback resulted in an impedance reduction (i.e., increase of transparency with respect to uncontrolled device) of about 30 dB over a frequency range of up to 10 Hz. In the range of 0-2 Hz, static friction and elasticity of the cable dominate the dynamics, whereas viscous friction dominates from 2-6 Hz and inertia at frequencies above 6 Hz. The admittance controller was able to render a minimal apparent mass of D kg[1] with the outer control loop closed over the USB DAQ card at 200 Hz, and the inner velocity loop controlled by a tachometer connected to a commercial linear power amplifier. As expected, the admittance controller can render higher output impedances, and - surprisingly - without any noticeable loss of transparency compared with the impedance controller. The lecture introduced the concepts of mechanical impedance, impedance control with force feedback and admittance control, and the Z-width plot as a valuable method to graphically represent the dynamic range of a pHRI device in different control modes.

[1] Determined from experimental data through multiple linear regression. Apparent mass of uncontrolled system: 0.4 kg.

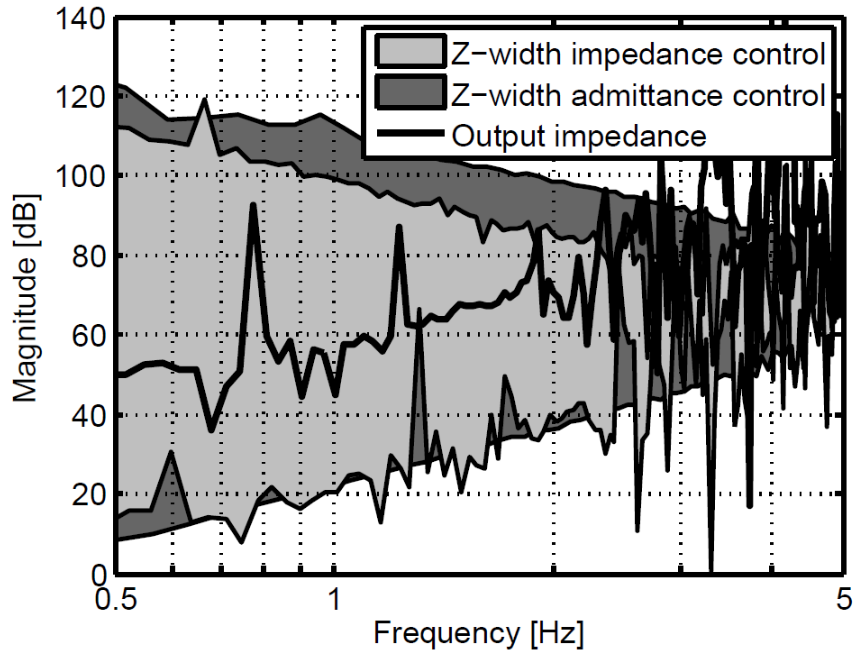

Fig. 3. Z-width of the ETHZ haptic paddle over a frequency range up to 5 Hz, representative for interaction with human motion. Shown are the output impedance of the uncontrolled device (bold line, center), maximum renderable output impedance (top) and minimal output impedance (bottom) for both impedance control with force feedback and admittance control. The oscillations in the impedance of the uncontrolled device and the impedance control with force feedback result from a non-homogeneous excitation of the device output over the frequency range up to 5 Hz.

B. Specialization Projects

Selected results are presented here from two of the nine specialization projects chosen by the students from the 13 available, Table II, in the fall semester of 2011; these further characterize the performance of the ETHZ haptic paddle.

1) Impedance Control with Force Feedback: Students assessed the accuracy of the rendered force of a virtual spring with the integrated force sensor, comparing the performance of an impedance controller without and with force feedback. While the effect is small as the uncontrolled haptic paddle is already quite transparent, Fig. 4

shows that the addition of force-feedback results in a significant shift of the rendered force towards that desired (reduction of the error by 58%), compensating for non-linearities of the system that were not modeled. The feedback gain of 1 was selected to achieve stable interaction. This nicely illustrates the concept and benefit of force feedback to students.

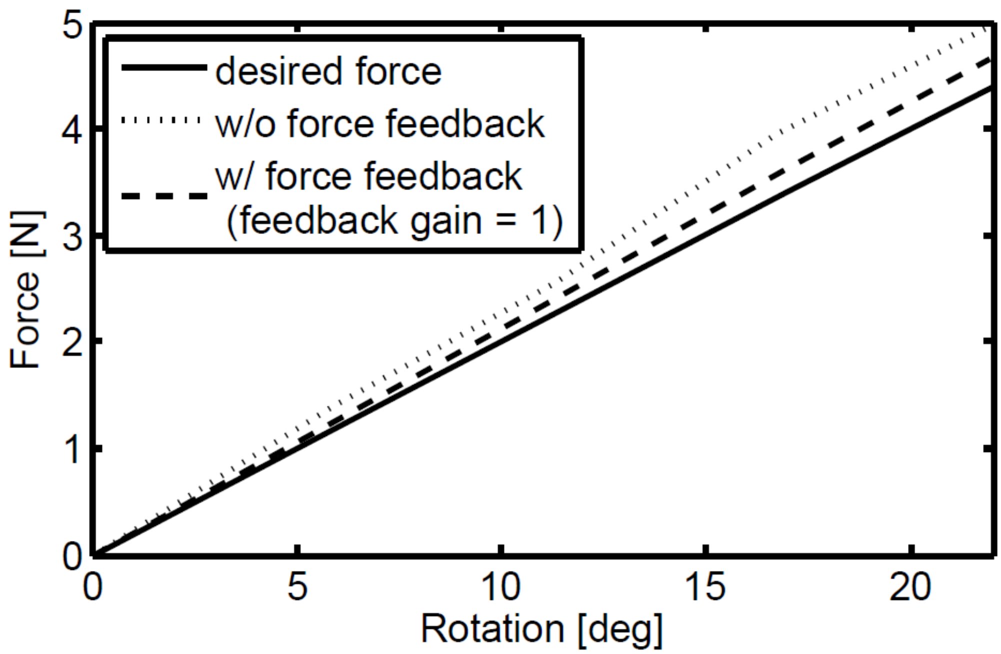

Fig. 4. Force feedback improves apparent stiffness towards the desired stiffness of a simulated spring. The plot shows the desired force, as well as the measured force for an impedance controller without and with force feedback.

2) *K-B Plots:* To evaluate the effects of quantization and discretization on the rendering of a stiff wall, the students selecting this project received an electro-optical encoder, mounted on the motor shaft, and a PCI data acquisition card, resulting in both higher resolution and sampling rates up to 500 Hz. Fig. 5 shows the K-B plots [30] obtained in the four possible combinations, i.e., Hall effect sensor vs electro-optical encoder at 100 Hz and 500 Hz sampling rate. While there is no noticeable effect for a

sampling rate of 100 Hz, a large increase in both the renderable stiffness and damping was achieved for a sampling rate of 500 Hz. While at lower sampling rates the phase shift resulting from the time delay dominates the limit of stability, the improved velocity estimation from the electro-optical encoder determines stability at higher sampling rates and allows for the rendering of higher virtual damping and thus also stiffness.

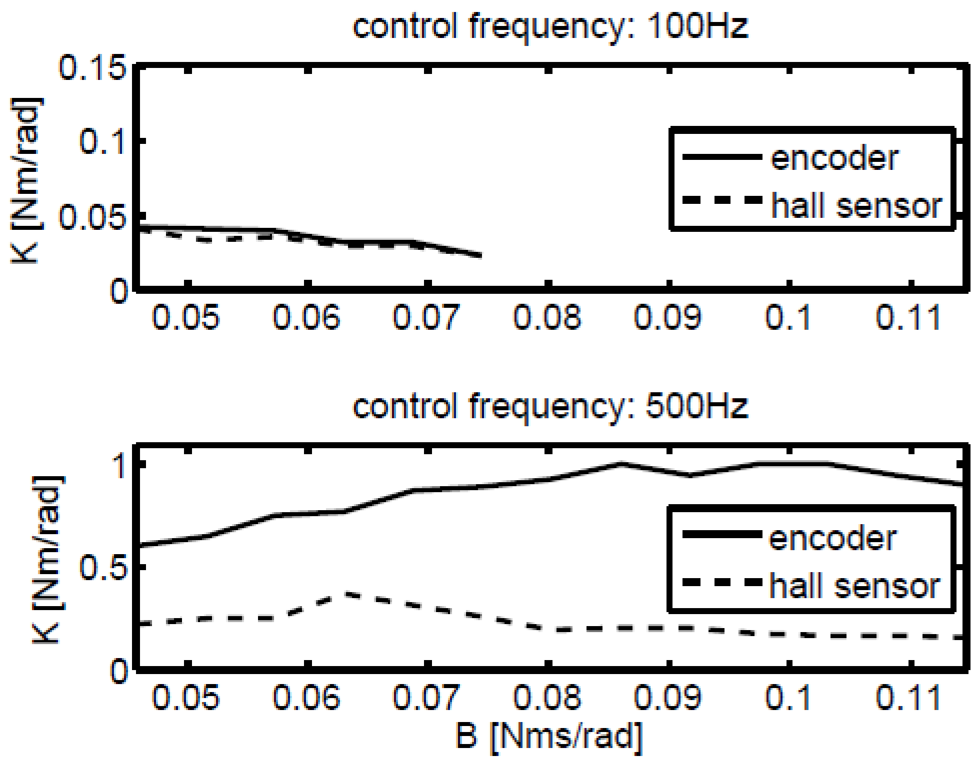

Fig. 5. K-B plots showing the increase of the stable rendering region of a virtual spring damper system (K-B values selected from underneath the curve result in stable rendering) through position measurement and velocity estimation with increased sampling frequency (500 Hz vs 100 Hz, both with a PCI DAQ card) from an electro-optical position encoder on the motor shaft compared to the hall sensor located on the paddle shaft. Note the different scales of the y-axes.

C. Observations of Student Learning

As this was a newly designed and delivered course, a comparison of learning outcomes with previous years or with the same course without the laboratory sessions is not possible. The success of the instructional design can, however, be assessed through the observed learning outcomes of the students in the laboratory sessions, the final presentation and in the oral exam. 17 out of 20 students had satisfactory or better competence in the learning objectives, and were able to correctly address the K5/K6 questions (high levels in the SOLO taxonomy), which is significantly above the authors' experience from other courses without laboratory sessions. Furthermore, several cases were experienced where students could write out equations but were unable to explain all of the terms. However, when prompted to recall how they proceeded in the corresponding laboratory session, these students could reconstruct their knowledge by combining it with their hands-on experience, and could eventually explain each term of the equations. Both these observations provide, in the authors opinion, evidence that the hands-on experience supported higher-order learning in the students.

D. Course Evaluation

The course was evaluated by the standard teaching evaluation form of the ETH Zurich rectorate, complemented by a standard set of questions formulated by the Department of Mechanical and Process Engineering [41] and an additional eleven questions specific to the course added by the authors. The questionnaires were anonymous and analyzed by the student administration of the Department of Mechanical and Process Engineering. Table III presents the results of selected questions from all three evaluation parts as well as the students' overall rating of the course (n = 16, mean ± SD, department mean ± SD in parentheses where available).

TABLE III

RESULTS OF THE TEACHING EVALUATION FORM COMPLETED BY STUDENTS ATTENDING THE PHRI COURSE (EXCERPT, **N=16**). 1: POOR / NOT AT ALL TRUE, 2: UNSATISFACTORY / ONLY MARGINALLY TRUE, 3: SATISFACTORY / PARTLY TRUE, 4: GOOD / MOSTLY TRUE, 5: VERY GOOD / ABSOLUTELY TRUE.

My overall impression of the quality of this course was:	4.7 ± 0.6 (3.8)
The lectures facilitated the students understanding of the course material.	4.4 ± 0.6 (3.7)
The haptic paddle is an adequate platform for the topics of this course.	4.8 ± 0.4
I liked the concept of the specialization projects (read literature, implement, evaluate, present).	3.9 ± 0.7
The specialization project allowed me to deepen my knowledge in pHRI.	4.1 ± 0.9
I would recommend this course to my colleagues.	4.9 ± 0.3
I could imagine working / performing research in this field someday.	4.0 ± 0.9
The course awakened my interest to conduct my Bachelor thesis at the Rehabilitation Engineering Lab.	4.3 ± 0.6
Mean of the 3 questions of the ETH Zurich Rectorate:	4.7 ± 0.2 (4.2 ± 0.3)
Mean of the 12 questions of the Department of Mechanical and Process Engineering, ETH Zurich:	4.3 ± 0.3 (4.0 ± 0.4)
Selected student comments: "The labs are a very good link between theory and practice, thanks!"; "Practical, finally…"	

IV. DISCUSSION

A novel course to teach the interdisciplinary topic of pHRI to upperclassmen engineering students in the Mechatronics Focus track of the Mechanical Engineering curriculum at ETH Zurich was designed. To make the theoretical concepts relating to dynamic systems, haptic control and human factors more tangible for students, the open-hardware haptic paddle was chosen/selected and adapted to the course, introducing new aspects such as a linear current amplifier as well as hardware variations, including an integrated force sensor for force feedback. The ETHZ haptic paddle is a transparent (i.e., intuitive) plug-and-play hardware setup controlled via commercial USB data acquisition modules, which students are likely to encounter throughout their academic or industrial careers. The use of a visual programming language also makes the laboratory sessions accessible to students with limited programming experience.

The introduction of specialization projects with hardware variations, dedicated laboratory time and project presentations during the last lecture of the course allowed students to investigate specific aspects of pHRI and communicate their insights to their classmates. The incorporation of a force sensor with the haptic paddle was a key enabler for many of the specialization projects, including advanced control strategies and performance evaluation. As the haptic paddle is intrinsically highly transparent (i.e., has low friction and reflected inertia), the improvement of transparency was assessed via a Z-width plot, showing a noticeable reduction of the apparent impedance in the range of 0-5 Hz, which covers the frequency range of typical hand movements like handwriting, typing and tapping [42].

Other courses at ETH Zurich have successfully employed hardware setups to teach digital control systems, embedded control systems and robotics and mechatronics, using inverted pendula, haptic wheels and SCARA-type robotic manipulators. While these courses focus more on traditional mechatronics and control aspects, a haptic paddle was used to transmit the interdisciplinary knowledge required for the development of rehabilitative and assistive robotic systems (such as an active knee prosthesis), and related control principles (such as impedance control with force feedback and admittance control). The hands-on tutorials with the haptic paddle allowed students to apply and quite literally grasp the theoretical concepts learned in this and other courses, and to complement this knowledge with insights on biomechanics, psychophysics and ergonomics (supported by points two and three in Table III). The ETHZ haptic paddle proved to be an adequate and robust platform for the laboratory sessions, with only one paddle and one Hall effect sensor being broken, although there was rather frequent slippage of the transmission cable and loosening of the force sensor fixation with use. The authors believe that the former performance limitation is an important component of the hands-on experience to be conveyed to students, while the latter has been resolved by replacing the piezoresistive force sensor with strain gauges glued to the paddle. Furthermore, the strain on the cable pretension unit of the paddle, which caused the one unit to break, was relieved by rounding the cutout for the pretension lever, as well as by shortening the pretension screw so that over-tensioning the mechanism becomes impossible, Fig. 1.

It is the authors' strong belief that the hands-on laboratory sessions were a crucial part of the pHRI course developed. At various times throughout the lectures and oral exams the authors perceived that students understood the underlying theory and could derive the dynamic equations but had difficulties relating the parameters to the behavior of a physical plant, which underlines the compartmentalization of knowledge and the difficulty of drawing connections between different facets of learning. However, a simple prompt to the appropriate part of the laboratory sessions helped students to activate their knowledge and answer questions requiring a high degree of knowledge synthesis (K5/K6 questions, high levels in the SOLO taxonomy) as opposed to simple "memorize and regurgitate" questions; answering with a level of detail beyond that which the authors have experienced in "traditional" courses. It is therefore concluded that the laboratory sessions played a crucial role in the achievement of the learning objectives.

The hands-on “learning by doing” approach as well as the group work and specialization projects were greatly appreciated by students, as also reflected by the very positive lecture evaluation. Six out of the twenty students who followed the pHRI lecture subsequently chose to perform their Bachelor’s thesis in the authors’ research group.

V. Conclusion

The ETHZ haptic paddle was successfully introduced in the undergraduate Mechatronic Focus track at the Department of Mechanical and Process Engineering at ETH Zurich, in the context of a new course on pHRI and proved to be a valuable educational tool. It is now also being used to teach students about position measurement and velocity estimation in pHRI as part of a first-year Bachelor’s tutorial in the new Health Science and Technology (HST) curriculum [43]. At the end of the lecture, students can connect their position measurement and velocity estimate to a spring/damper module provided, allowing them to feel various levels of stiffness and damping.

This pHRI course was put together as a pilot study, from which many lessons have been learned with respect to the lectures, laboratory sessions, course materials, as well as the hardware employed. This experience will be used in expanding the course at ETH Zurich in the coming semesters, with the aim of providing students with even more opportunities to combine their knowledge in various ways, and to break down the divisions between disciplines. The course is also being transferred to the Ecole Polytechnique Fédérale de Lausanne (EPFL) in Lausanne, Switzerland, to be taught from the spring semester of 2013 with a stronger mechatronics and medical robotics focus, adapted to the local Micro-Engineering curriculum. It is also planned that the full lecture and the laboratory sessions be offered in the Health Science and Technology curriculum at ETH Zurich in the future, with a stronger focus on motor physiology and motor neuroscience.

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