Physical Human-Robot Interaction Using HANDSON-SEA: An Educational Robotic Platform with Series Elastic Actuation

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***Abstract*—For gaining proficiency in physical human-robot interactions, it is crucial for engineering students to be provided with the opportunity to gain hands-on experience with robotic devices that feature kinesthetic feedback. We propose HandsOn-SEA, a low-cost, single degree-of-freedom, force-controlled educational robot with series elastic actuation and introduce educational modules for the use of the device to allow students to experience the fundamental performance trade-offs inherent in robotic systems. The novelty of the proposed robot is due to the deliberate introduction of a compliant element between the actuator and the handle, whose deflections are measured to perform closed-loop force control. As an admittance-type robot, HandsOn-SEA relies on force feedback to achieve the desired level of safety and transparency and complements the existing impedance-type educational robots. We present the integration of HandsOn-SEA into the robotics curriculum, by providing guidelines for its use in a senior level robotics course, to help students experience the challenges involved in the synergistic design and control of robotic devices. We systematically evaluate the efficacy of the device in a robotics course delivered for five semesters and provide evidence that HandsOn-SEA is effective in instilling fundamental concepts and trade-offs in the design and control of robotic devices.**

***Index Terms*—Physical Human-Robot Interaction (pHRI), Series Elastic Actuation (SEA), Educational Robotics, Interaction Control**

I. INTRODUCTION

Establishing natural and safe physical human-robot interactions (pHRI) is an active research area. A thorough understanding of such interactions can be the basis of successful applications in many areas, including service robotics, surgical, assistive and rehabilitative robotics, haptics and teleoperation. Therefore, it is important for engineering students to have the opportunity to physically interact with robots to gain hands-on experience in their design and control.

Hands-on experience is known to be crucial in strengthening the understanding of basic engineering concepts [1]. *Haptic paddles* [2]—single degree-of-freedom (DoF) devices with kinesthetic feedback—have been successfully utilized as effective teaching platforms for several system dynamics and controls classes in many universities around the world [3]. As educational tools, all haptic paddles share the common design features of simplicity, robustness and low cost. Design simplicity allows students to easily understand the working principles, while robustness and low cost enable their accessibility and availability for large groups of students.

In this paper, we introduce an educational force-feedback robot and provide guidelines for the educational use of the device to demonstrate the synergistic nature of mechanical design and control in robotic devices. We also present a set of laboratory assignments that allow students to experience the interdependency of design choices in the mechatronic design of robotic systems. These laboratory assignments require students to modify the mechanical system, in addition to its controller and characterize the effects of these design decisions on the closed-loop control performance of the educational device. We evaluate the efficacy of introducing HANDSON-SEA into robotics education by testing the device in a senior level robotics course delivered over five semesters and provide evidence that the device is effective in providing experience on fundamental concepts in robot control and instilling in a strong understanding of fundamental trade-offs in the design and control of force-feedback robotic devices. In comparison to its preliminary conference version [4], this paper details the mechatronics design, control, and performance of the device; significantly extends the guidelines for its educational use; evaluates the instructional design of the laboratory sessions through the achievement of course learning outcomes; and provides a systematic long-term evaluation of student performance and a comparison of this performance to a control group.

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II. RELATED WORK

A. Design of Educational Devices with Haptic Feedback

Several open-hardware designs concerning force controlled robots exist in the literature. A pioneering educational force controlled robot designed for kinesthetic feedback is the *haptic paddle* [2]. The haptic paddle is a single DoF impedance-type device that features passive backdrivability and excellent transparency, thanks to its low apparent inertia and negligible power transmission losses. In the original design, a Hall effect sensor is used to sense rotations, while a custom built (analog) linear current amplifier is utilized to avoid torque ripple associated with PWM type motor drives. Other important design features of the haptic paddle are its robust design and low cost, thanks to utilization of common off-the shelf parts and simple rapid prototyping methods for its construction.

The success of this design has led to several different versions of the haptic paddle [5]–[10]. The original haptic paddle design relies on a capstan drive. However, the maintenance of the capstan transmission after cable stretch, fall-off or break is a tedious task, especially for an educational setup. To address these problems, the capstan transmission of the original design has been replaced by a custom built direct drive voice coil actuation in iTouch [5], [11], while a friction drive transmission has been adapted in [8].

In [6], improvements have been implemented to increase the design robustness and to decrease the manufacturing cost of haptic paddle. Further design iterations have been undertaken in [7], [9], [10], where especially the underlying electronics and control interface have been modified and updated. In particular, most of the earlier designs rely on PC based I/O cards and linear current amplifiers, while analog controller circuits are utilized in [5]. A PWM voltage amplifier and an Atmel processor (Arduino) based micro-controller are adapted in [8], trading-off the fast control rates of PC based controllers and torque control performance of linear current amplifiers with a more compact and low cost control/power electronics infrastructure. A recent iteration of these designs, the Hapkit [10], further customizes the control/power electronics infrastructure proposed in [8] and adds a force sensitive resistor to the device handle.

Haptic paddles aim at establishing safe and transparent pHRI. To achieve these goals, all of the designs reported in the literature rely on low inherent output impedance of the mechanical device. In particular, all of the existing haptic paddle designs are of impedance-type, possessing passive backdrivability thanks to their low friction power transmissions and low apparent inertia. Such impedance-type devices are commonly preferred for haptic interactions, since these devices can achieve high force control fidelity even with open-loop force control, that is, without the need for force feedback.

While HANDSON-SEA preserves the simplicity, robustness and low cost of other designs, as an admittance-type robotic device, it is fundamentally different from and complementary to all of the existing haptic paddles, as force feedback is an inherent design feature of HANDSON-SEA. Thanks to its integrated force estimation mechanism, HANDSON-SEA can utilize force feedback to modulate its output impedance for high fidelity haptic rendering. Due to its high transmission ratio, HANDSON-SEA is capable of rendering large forces at its handle, producing strong kinesthetic feedback that is easily differentiable by its users. As a result of its integrated force sensing element, HANDSON-SEA is inherently compliant, resulting in safe interactions even under impacts. The stiffness of the compliant element has a direct and observable effect on the performance of HANDSON-SEA and this compliance needs to be considered as part of its dynamic model and model based controllers.

B. *Evaluation of Educational Devices with Haptic Feedback*

Haptic paddles have been adopted to engineering curriculum by several universities [3]. The first investigation of a haptic paddle type device in a classroom/laboratory environment was conducted in [2]. In this work, haptic paddle has been proposed to support the learning process of students who have dominant haptic cognitive learning styles. The device was used for an undergraduate course on dynamic systems for a semester at Stanford University. The laboratory exercises included motor spin down test for observing the damping effect, bifilar pendulum test for understanding the components of the dynamic system, sensor calibration and motor constant determination, impedance control and virtual environment implementations. The laboratory modules of this work have formed a basis for other courses taught in different universities. The effectiveness of the haptic paddle was measured by a student survey and it has been observed that the device helped students to better grasp engineering concepts.

At the University of Michigan, force controlled devices iTouch and Box were used in engineering undergraduate courses [5]. In a mechanical engineering course, the device was used to support the learning of students about concepts such as frequency domain representations, dynamical system modeling and haptic interactions. In an electrical engineering course, students were introduced to integrating sensors and actuators to micro-controllers, learned about hybrid dynamical systems and improved their programming skills.

Haptic paddle was also used in an undergraduate system dynamics course at Rice University [6], [12]. The use of the device aimed to improve the effectiveness of the laboratory sessions and to introduce students to haptic systems, where virtual environments can be used to assist the teaching of complex dynamics phenomena. In [6], student understanding of engineering concepts and fundamentals was quantified through a 16-item grading rubric during two semesters: a semester with traditional laboratory sessions disjointed from the course material and another semester during which haptic paddle was introduced to conduct a cohesive set of laboratory exercises. Results indicated important gains in student understanding with the integration of cohesive set of laboratory exercises with haptic paddles. In [12], a formal analysis was conducted over two semesters to investigate the effect of inclusion of reflective learning activities implemented through pre- and post-lab discussions. Performance was quantified through rubics, homework, laboratory, and final exam grades. Statistical analysis revealed that laboratory exercises with reflective learning activities resulted in statistically significant performance increase on the overall laboratory grades. While a significant effect was not shown for the final grades, reflective learning activities improved standard deviations and resulted in higher lowest grades.

Another systematic evaluation of integrating haptic paddle in an undergraduate level pHRI course has been conducted in [7]. The pHRI course covered the effect of having a human in the loop, the design methodology for pHRI systems, system identification for the robotic devices, force controller design and assessment of the robot performance in terms of psychophysical metrics. Laboratory sessions included the implementation of open-loop and close-loop impedance controllers, gravity and friction compensation methods, and interaction controllers. Moreover, students were asked to complete course projects that combined the concepts they learned throughout the lectures. The effectiveness of the haptic paddle based instruction was measured by student evaluation surveys, oral exams and student presentations. It has been observed that hands-on learning was beneficial for pHRI and laboratory sessions can help students achieve higher degree of knowledge synthesis according to the Structure of Observed Learning Outcomes (SOLO) taxonomy. Furthermore, students' evaluations of the device were positive, while the instructors observed an improved success rate in their exams.

Haptic paddle has also been used in an undergraduate system dynamics course at Vanderbilt University [8]. The laboratory sessions included analyzing first and second order system models, determining equivalent mass, damping and stiffness of these systems, exploring friction/damping and other external disturbances and observing their effects on the output of the system, experiencing the forced responses of vibratory systems, and implementing several closed-loop controllers. A formal assessment of student learning due to haptic paddle integration to the course was conducted over three semesters. To quantify student learning, assessments were administered before and after each semester. Furthermore, to determine the timing of learning, five multiple choice quizzes were administered in a randomized manner, before the lab, after the pre-lab, after the lab and after completing the lab report. Results showed a statistically significant difference with a large effect size between the cumulative scores at the beginning and at the end of the semester evaluations, indicating that students have gained a better understanding of and displayed better retention rates for the majority of the core concepts they learned throughout the course via all learning opportunities. The statistical analysis also revealed that supplementing the in-class lectures with laboratory sessions as a whole (including pre-lab, during lab, and lab report activities) enhanced student understanding of the material.

The Stanford haptic paddle, called Hapkit, has been integrated as the main experimental setup in a massive open online course made accessible all around the world [10]. A newer version of Hapkit has also been used to teach physics in secondary education [13].

HANDSON-SEA complements all of these existing haptic paddles, not only in terms of its mechatronic design, but also as an educational tool, by enabling students to experience force-feedback control architectures for pHRI, and by demonstrating the synergistic design challenges involved in the mechatronic design of robotic devices. While HANDSON-SEA can be used to administer the laboratory exercises during a systems dynamics course as proposed in [2], [6], the unique design of HANDSON-SEA enables it to be used to demonstrate the interdependent nature of the plant and the controller dynamics on the system performance by allowing students to modify the plant in addition to its controller and characterize the effects of these design decisions on the closed-loop system performance. HANDSON-SEA is also effective tool to study the fundamental limitations of feedback control via demonstrations of strict stability limits under the non-collocation between the sensor and the actuator. HANDSON-SEA has been integrated into robotics education and has been under continual use in a classroom setting since 2016 [4].

III. Design and Implementation of HandsOn-SEA

In this section, we detail the mechanical design, instrumentation and power electronics/control of HandsOn-SEA, a low-cost, single DoF educational robot with series elastic actuation (SEA). The design and controllers have been developed to promote a do-it-yourself philosophy [14]. All the design files and the software required to implement and operate HandsOn-SEA, as well as the assignments, laboratory manuals, and video demonstrations, are shared at https://github.com/HMILab/HandsOnSEA under MIT General Public License. Files are regularly being updated for wider availability, lower manufacturing cost, and better robustness. Furthermore, open-source hardware allows end users to share, customize, and improve designs.

A. Mechanical Design and Power Transmission

The main actuation mechanism and dimensions of HandsOn-SEA, as presented in Figure 1, have been designed to be compatible with existing haptic paddle designs, such that existing devices can be equipped with SEA with minimal modifications. To enable built-in force sensing, the sector pulley, which is common to almost all haptic paddle designs, has been modified to feature a compliant joint element and a position sensor to measure deflections of this compliant element.

In particular, the monolithic rigid sector pulley-handle structure has been manufactured in two parts: the handle with a Hall effect sensor and the sector pulley with two neodymium block magnets. The handle is attached to the device frame through a ball-bearing, and the sector pulley is attached to the handle through a cross-flexure pivot. A cross-flexure pivot, formed by crossing two symmetrical leaf springs, is a robust and simple *compliant* revolute joint with a large range of deflection [15], [16]. A cross-flexure pivot is preferred as the compliant element of the SEA since this leaf-spring type compliant pivot distributes stress over its entire length and provides robustness by avoiding stress concentrations that are inherent in notch-type compliant elements. The center of rotation of the cross-flexure pivot is aligned with the rotation axis of the handle, while the Hall effect sensor is constrained to move between the neodymium block magnets embedded in the sector pulley.

As in haptic paddle designs, the sector pulley of the device can be actuated by a capstan drive or a friction drive transmission. In our current prototype, we prefer to use a friction drive power transmission, since it is more robust and easier to maintain. Furthermore, even though it has been shown that friction and slip due to friction drive transmission can significantly decrease the rendering performance of haptic paddle devices operating under open-loop impedance control [9], these parasitic effects caused by the low quality power transmission element can be more effectively compensated by the robust cascaded control architecture of SEA [17].

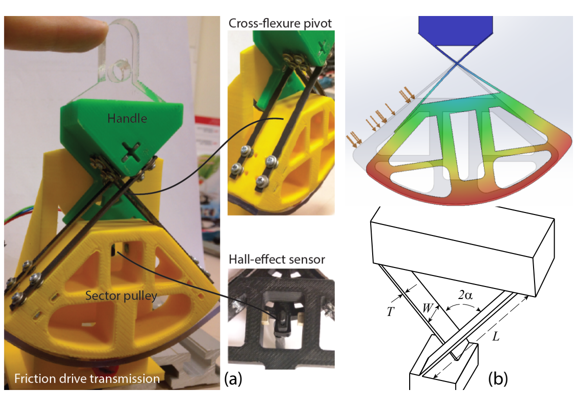

Fig. 1: a) HandsOn-SEA – A single DoF series elastic educational robot b) An exaggerated finite element model of the proposed compliant element and its schematic representation with parameters

Our current design employs a surplus geared coreless DC motor (Maxon RE 13 with 84:1 gearbox) equipped with an encoder together with a friction drive to impose desired motions to the sector pulley. In order to keep the manufacturing simple and low cost, all the mechanical components of the educational robot, except for the sheet metal parts and the bearing, are designed to be suitable for construction using additive manufacturing techniques. The design consists of simple planar parts that can be fabricated using low cost methods, such as laser cutting. A capstan drive version of HandsOn-SEA with an alternative low-cost DC motor, as well as multi-DoF versions inspired by [11], are presented in [14].

B. Sensors and Power Electronics

HandsOn-SEA necessitates two position sensors: one for measuring the motor rotations and another for measuring the deflections imposed on the elastic element. Since the surplus DC motor used readily includes a magnetic encoder, this sensor is used for measuring motor rotations and estimating motor velocities. The deflections of the cross-flexure pivot are measured using a Hall-effect sensor (Allegro MicroSystems UNG3503). A simple and low cost Hall-effect sensor is appropriate for measuring these deflections, since the required range for measurements is small, resulting in robust performance. Furthermore, from a pedagogical point of view, this choice enables students to gain experience in integrating both analog (Hall effect) and digital (magnetic digital encoder) sensors into the control system.

A low cost PWM voltage amplifier (TI DRV8801 H-bridge motor driver with carrier) is utilized to drive the DC motor. Unlike the impedance type haptic paddle designs, this selection is not a compromise solution for our design that trades-off performance for cost effectiveness. On the contrary, a PWM voltage amplifier is a natural choice for the cascaded loop control architecture of SEA, since the velocity (not the torque) of the motor is controlled by the inner motion control loop and any high frequency vibrations (possibly induced by PWM) are mechanically low-pass filtered by the compliant element before reaching to the user.

C. Micro-Controller

We have implemented controllers for the series elastic robot using a low-cost micro-controller, TI C2000 (LaunchpadXL-F28069M). We have interfaced HandsOn-SEA with and implemented its cascaded loop controller using TI Launchpad, since this cost effective industrial grade controller can decode quadrature encoders and can be used to effectively estimate velocities from encoder measurements. Furthermore, this micro-controller can be programmed through the Matlab/Simulink graphical interface, and allows for easy prototyping of (multi-rate) control architectures with hard real-time performance.

IV. Modeling and Control of HandsOn-SEA

A. Stiffness of the Cross-Flexure Pivot

Figure 1(b) presents a schematic model of the cross-flexure pivot. Five parameters govern the deflection and stiffness properties of a cross-flexure pivot: The length L, the thickness T and the width W of the leaf springs, the angle 2α at the intersection point of the leaf springs and the dimensionless geometric parameter $\lambda \in [0, 1]$ that defines the distance of the intersection point of leaf springs from the free end. Given these parameters, the torsional stiffness K_τ of the cross-flexure pivot can be estimated as follows [16], [18], where E is the modulus of elasticity and I is the second moment of area.

$$K_\tau = 8(3\lambda^2 - 3\lambda + 1)\frac{EI}{L} \tag{1}$$

TABLE I: Parameters Used for Dynamic Modeling

J_a – inertia of the motor	1.3	gr-cm^2
J_g – inertia of the gearhead	0.05	gr-cm^2
J_h – inertia of the handle about the bearing	1.93	gr-cm^2
J_p – inertia of the sector pulley about the bearing	14.7	gr-cm^2
r_g – gearhead reduction ratio	84:1	
r_c – capstan reduction ratio	73:9	
k_f – stiffness of the cross flexure pivot	4000	N-mm/rad
R – motor resistance	10.7	Ohm
b_m – cumulative damping of the motor	0.025	N-mm/s
K_m – motor torque constant	16.2	mN-m/A
K_b – motor back-emf constant	61.7	rad/sec/V
τ_m – mechanical time constant	5.31	ms

B. Dynamic Model

The series elastic robot can be modeled as a single link manipulator actuated by a DC motor. Table I defines and lists the parameters that are relevant for dynamical modeling of HANDSON-SEA.

The motion of the DC motor is controlled by regulating its voltage. Since the electrical time constant (0.042 ms) of the DC motor is two orders of magnitude lower than its mechanical time constant (5.31 ms), the transfer function from motor voltage $V(s)$ to motor velocity $s\theta_m(s)$ can be derived as

$$\frac{s\theta_m(s)}{V(s)} = \frac{K_m/R}{Js+b} \tag{2}$$

where $J = J_m + J_g + J_p/(r_g r_c)^2$ and $b = b_m + K_m K_b/R$. Note that we have neglected the inertial contribution of the handle, since its inertia J_h is also orders of magnitude smaller than the reflected inertia of the motor side of the cross-flexure pivot. Neglecting the inertial contributions of J_h, the torque τ_h measured by the flexure acts on the system according to

$$\frac{s\theta_m(s)}{\tau_h(s)} = \frac{-1/(r_g r_c)}{Js+b} \tag{3}$$

where the rotation of the pulley is related to the motor rotation by $\theta_p(s) = \theta_m(s)/(r_g r_c)$. Unmodeled dynamics of the system are considered as disturbances that act on the system. Robust motion control of the DC motor is used to compensate for these disturbances.

C. Cascaded Loop Controller

The SEA controller is based on cascaded control loops, which has first been proposed in [19] and later rediscovered in [20], [21]. In this approach, also called velocity-sourced impedance control (VSIC), the inner loop of the control structure employs a robust motion controller to compensate for the imperfections of the power transmission system, such as friction, stiction and slip, rendering the motion controlled system into an ideal velocity source within its control bandwidth. The intermediate control loop incorporates force feedback into the control architecture and ensures good force tracking performance under an adequately designed inner loop. Finally, the outer loop determines the effective output impedance of the system.

For the cascaded control architecture, the controller parameters are selected according to [17], [22], [23]. These control parameters satisfy the necessary and sufficient conditions for frequency domain passivity of the system during null space and stiffness rendering and ensure coupled stability of interactions with SEA.

Table II summarizes the experimentally characterized technical specifications of HANDSON-SEA. The velocity, small force and large force bandwidths of HANDSON-SEA are verified to be 14 Hz, 12 Hz, and 7 Hz, respectively. Characterizations with a commercial force sensor (ATI Nano 17) verify these results and indicate that steady state error for HANDSON-SEA is less than 5% for set-point force control, while the force tracking RMS error of HANDSON-SEA is characterized as 7.6% for a chirp signal up to 3 Hz.

TABLE II: Technical Specifications of HANDSON-SEA

Continuous Force Output at the Handle	15	N
Deflection Sensing Resolution (Hall)	0.2	mm
Force Sensing Resolution	0.05	N
Workspace	± 40	°
Nominal Speed at Gear Output	145	rpm
Velocity Control Bandwidth	14	Hz
Small Force Bandwidth	12	Hz
Large Force Bandwidth	7	Hz

V. LABORATORY ASSIGNMENTS WITH HANDSON-SEA

HANDSON-SEA has been designed to enable students to experience the synergistic coupling between the plant and the controller dynamics on the overall performance of mechatronic systems. Series elastic actuators are inherently multi-domain systems whose performance depends on the design of both the plant and the controller [24]. Hence, these devices are well suited for demonstrating the challenges involved in the design of robotic systems and instilling in the importance of concurrent design thinking to achieve the best performance from mechatronic devices.

The senior level *Introduction to Robotics* course at Sabanci University is designed to equip students with the fundamental theories and the computational methodologies that are used in design and analysis of robotic systems. Students learn how to analytically formulate kinematic and dynamic equations for robot manipulators, how to model actuator and drive train dynamics, synthesize trajectory tracking and interaction controllers, as well as how to utilize numerical algorithms to simulate and real-time hardware-in-the-loop controllers to implement such closed-loop control systems. The emphasis in the course is an integrated understanding of the kinematic/dynamic modeling and control concepts for robotics.

In the control part of the robotics course that utilizes HANDSON-SEA, students are first introduced to fundamental limitations imposed due to the non-collocation of sensors and actuators. It is noted that while non-collocation arises in motion control systems with drive train dynamics, this limitation is inherent to all causal systems with force feedback [25]–[27]. After the introduction of the fundamental limitations, the concept of series elastic actuation is explained as a trade-off between the sensor stiffness and controller gains, emphasizing the interdependence of the mechanical and controller design.

It is noted that SEA trades-off large force-control bandwidth for force/impedance rendering fidelity, by using compliant force sensing elements in the force control framework [19], [28]. By decreasing the force sensor stiffness and utilizing a model of the compliant element, higher force-feedback controller gains can be utilized to achieve responsive and robust force-controllers within the control bandwidth of the system. It is explained that SEA possesses favorable output impedance characteristics, allowing it to be safe for human interaction over the entire frequency spectrum. In particular, within the force control bandwidth of the device, SEA can ensure backdrivability through active force control, that is, by modulating its output impedance to the desired level. For the frequencies over the control bandwidth, the apparent impedance of the system is limited by the inherent compliance of the force sensing element, which acts as a physical filter against impacts, impulsive and high frequency disturbances (such as torque ripples). The main disadvantage of SEA is emphasized as its relatively low large-force bandwidth, caused by actuator saturation due to significant sensor compliance.

A set of laboratory assignments have been developed as six main modules to complement the theoretical concepts covered in the *Introduction to Robotics* course. The laboratory sessions were held under the supervision of two graduate students who helped to solve any technical problems, spark pre- and post-lab discussions, and encourage equal participation by group members. After the basic concepts have been covered during lectures, students were given pre-laboratory assignments to complete as a warm-up to key concepts before they attended the laboratory sessions.

The course learning outcomes (CLO) for these laboratory sessions are defined as: "By the end of the laboratory sessions, students will be able to model actuator and drive train dynamics, synthesize trajectory tracking and interaction controllers (*CLO-1*), and utilize numerical algorithms to simulate, and real-time hardware-in-the-loop controllers to implement closed-loop control systems (*CLO-2*)."

The laboratory modules can be summarized as follows:

Module 1: This module is designed to study the modeling, control, and experimental characterization of a single DoF dynamic rigid body system under motion control. In the pre-laboratory assignments to be completed before this module, students reviewed the concepts of transfer functions, root-locus and Bode plots.

During this module, firstly, the students derived the second order rigid body model of the plant with the DC motor and investigated the theoretical stability limits of the motion controlled system through a root-locus analysis. They concluded that instability is not expected even for high controller gains, since the root-locus plot of the position controlled rigid-body model has two asymptotes. They determined the theoretical controller gains to achieve a pre-determined bandwidth with no overshoot.

Secondly, students implemented a PI velocity controller for the motor of HANDSON-SEA and tried the controller gains they had calculated analytically. They empirically tuned their controllers to achieve the fastest stable non-overshooting step response. They were asked to discuss possible reasons of instability they experienced for large gains during the physical implementation of the controller.

Actuator bandwidth limitation, unmodeled dynamics of the device, sampling-hold effects and sensor noise were explained as some of the potential factors behind the practical gain limits. The effect of bandwidth limitation due to the saturation of the actuator was demonstrated using a first order low-pass filter at the actuator input in simulation and with a root-locus analysis.

In the final step, students collected data with the empirically tuned gains and drawed a Bode plot of the system to determine the closed-loop velocity control bandwidth of the device. It was discussed that, up to this frequency, the robot can be regarded as a perfect velocity source, as necessitated by the force and impedance control loops.

Module 2: This module is designed to demonstrate the fundamental stability limits of closed-loop control systems that possess sensor actuator non-collocation. In the pre-laboratory assignments, students studied non-collocated motion control of systems with drive train dynamics and were exposed to explicit force control.

During this module, the students implemented an explicit force controller by utilizing the force feedback obtained by measuring the deflections of the series elastic element. While testing this controller, students experienced that the control gains need to be kept low, not to induce instability and chatter during contacts. This phenomenon was attributed to the non-collocation between the force sensor and the motor, and students were asked to model this non-collocation by a linear model that captures the first vibration mode of the system.

Root-locus analyses enabled students to observe that non-collocation introduces two poles and one zero to the system, thus an additional asymptote, which causes the close loop poles to become unstable for high loop gains. Students also analysed two alternative linear models that result from introducing compliance to the robot base or the environment. In these analyses, they observed that the same number of poles and zeros are introduced to the system. Upon finishing this module, students were expected to convince themselves that the instability was caused by the compliance specifically located between the actuator and the sensor.

Module 3: This module is designed to provide students with an understanding of the interdependent nature of plant and controller dynamics in the design of robotic systems. Along these lines, the fundamental trade-off between the physical sensor stiffness and the maximum stable force controller gain is studied.

In the pre-laboratory assignments, students were introduced to the analytical stiffness model of the cross flexure joint and reviewed root-locus based stability analysis of force controlled systems with non-collocation.

During this module, firstly, students calculated the stiffness of the two different flexure joints. One of the cross flexure joints featured two leaf springs with $\lambda = 0.5$ and possessed a low stiffness. The other cross flexure joint featured four leaf springs with $\lambda = 87.3\%$, had low center shift, better lateral stability, and significantly higher stiffness. In general, capstans with different stiffness levels can be implemented by simply changing the thicknesses and/or the number of the leaf springs used to form the compliant joint.

Secondly, students utilized the cross flexure joint with higher stiffness in an explicit force controller to empirically determine the maximum controller gain that can be used without inducing instability or chatter during contacts. The same procedure was repeated for the cross flexure joint with lower stiffness. The loop gains were computed for both cases, such that students could experimentally verify that decreasing the force sensor stiffness enabled them to increase the force controller gains. Finally, the advantages and disadvantages of using a more compliant force sensor were discussed, from the perspectives of the coupled stability and force control performance.

Module 4: This module is designed to study the SEA concept and trade-offs involved in their design. Furthermore, this module provides hands-on experience with SEA to demonstrate the output impedance characteristics and the bandwidth of these systems.

In the pre-laboratory assignments, the underlying idea of SEA was explained as the reallocation of limited loop gain of the non-collocated force control system, implemented by decreasing the physical force sensor stiffness by a few orders of magnitude, such that the force controller gain can be increased by a similar amount. It was noted that higher feedback controller gains are preferred to achieve fast response times and good robustness properties to compensate for hard to model parasitic effects, such as friction and backlash. The trade-off involved in this decision was also emphasized by a discussion of the actuator saturation and bandwidth limitation arising due to the use of a more compliant force measurement unit. The output impedance transfer function of the system was derived and its Bode plot was studied to characterize the system behaviour at low and high frequencies.

During this module, students implemented an actively backdrivable system by setting the desired force in the explicit force controller to zero. Next, they pushed the handle of the device with low, intermediate and high frequency (impulsive) inputs. The same procedure was repeated when the controller was turned off. The students were asked to comment on the changes they experience in the output impedance with the gradual increase in frequency for both cases.

Next, students applied high frequency torque ripples through the motor while holding the handle to experience the low pass filtering behaviour of SEA. They also plotted the data collected by the force sensing element during this input and compared it with the torque ripple input, to better visualize the filtering effects. Finally, students implemented and characterized set point controllers to determine the force control performance of SEA.

Module 5: This module is designed to introduce the cascaded controller architecture for SEA and to evaluate the rendering and force tracking the performance of the device under VSIC.

In the pre-laboratory assignments, the rationale behind the cascaded controller was explained. The necessary and sufficient conditions for the controller gains to ensure coupled stability of the system are also briefly discussed as in [17], [22], [23].

During this module, students implemented impedance controllers with the cascaded control architecture, to render free space, virtual walls and a mass-spring-damper system, respectively. In particular, in the cascaded controller, the desired impedance was set to zero for free space rendering, such that the system tried to achieve ideal active backdrivability. The desired impedance was set to that of relatively stiff unidirectional springs to render virtual walls. During stiffness rendering, through attachment of a sufficiently large mass to the handle, it was demonstrated that the stiffness of the virtual wall cannot be set higher than the stiffness of the cross flexure joint, to ensure coupled stability of interaction. The desired impedance was set to a second order system dynamics to render a mass-spring-damper system. Students were asked to compute the natural frequency of the virtual mass-spring-damper system and verify through physical interaction that the virtual system had a resonance at this frequency. To complement haptic rendering exercises, animations were provided to students to help them visualize the dynamical system that governed the haptic feedback. Finally, students were asked to characterize the force tracking the performance of SEA for chirp reference signals.

Module 6: This module aims to demonstrate the performance trade-offs of SEA by letting students characterize the closed-loop force control bandwidth of the device under various loads.

In the pre-laboratory assignments, students reviewed the experimental determination of Bode plots. The concept of small and large force bandwidths were introduced, and the trade-offs involved in the determination of the stiffness of the SEA were discussed.

During this module, students experimentally characterized the small and large force bandwidths of the device by providing sinusoidal references to the system and recording its response, for force references of various magnitudes. Students were expected to experience a decline in the system bandwidth as the magnitude of the desired force increases. The effect of actuator speed saturation was emphasized as the underlying reason. Increasing the sensor stiffness, decreasing the damping in the system, and increasing the velocity bandwidth of the actuator were discussed as possible remedies.

VI. Evaluation of Educational Efficacy

The educational effectiveness of the laboratory assignments has been evaluated through student surveys, course learning outcomes and student performance measured at the final exam.

A. *Student Evaluations of* HandsOn-SEA

We have used HandsOn-SEA while teaching the *Introduction to Robotics* course at Sabanci University during Spring 2016, Fall 2016, Fall 2017 and Fall 2018 semesters. These 4 semesters included 81 students with mechatronics background, while 46 students who took the course during Spring 2015 semester served as the control group. The course has been taught in all of these five semesters by the same instructor, while the laboratory assignments with HandsOn-SEA as detailed in Section V have been integrated into the curriculum from Spring 2016 onwards. As a pre-requisite of the course, all of the students had completed at least one course on system dynamics and one course on feedback controls; but none of them had any background on force control or SEA.

During the laboratory sessions of the course, Modules 1–6 were implemented utilizing HandsOn-SEA. The course also included lectures that cover relevant technical concepts in these modules, weekly recitation hours, and pre-laboratory assignments. After the course, all students filled in an anonymized questionnaire. The questionnaire includes 5 questions: Q1 is aimed at evaluating the background required by the students, Q2 is for assessing the useability of the device, Q3 is for determination of target population for its educational use, and Q4–Q5 are for assessing the useful aspects of HandsOn-SEA. For Q1 and Q2, the participants were allowed to choose all responses that apply, while for Q3–Q5, five-point Likert scale, ranging from "1" *strong disagree* to "5" *strong agree*, has been used to measure the agreement level of the participants.

TABLE III: Survey Questions and Summary Statistics

Q1: What kind of knowledge and skills did you require to use HandsOn-SEA?

	Frequency
Knowledge of modeling dynamical systems	66.8%
Knowledge on controls theory	73.5%
Familiarity with hardware-in-the-loop	68.9%
Experience with real-time controllers	64.3%
Experience with motor drivers	56.1%
Experience with integrating sensors	55.5%
Experience in programming	54.6%

Q2: Which one of the following aspects of HandsOn-SEA do you find important?

	Frequency
Easy to use	77.8%
Simple working principle	76.0%
Robust	68.3%
Low cost	82.4%
User friendly	70.9%
Easy to build and maintain	78.1%

Q3: How would you rate the usefulness of HandsOn-SEA for the following groups?

	Mean = 3.94	σ^2 = 1.02
Mechatronics juniors and seniors	4.40	0.92
Mechatronics graduates	4.31	0.88
High school students	2.10	1.21
Robotics researchers	4.10	1.02

Q4: How useful were HandsOn-SEA in helping with the following concepts and trade-offs?

	Mean = 4.12	σ^2 = 0.91
Compliant mechanisms	4.15	0.93
Sensor actuator non-collocation	4.18	0.88
Fundamental limitations of force control—compliance-gain trade-off	4.30	0.83
Admittance control	4.23	0.89
Series elastic actuation	4.17	0.99
Backdrivability and output impedance	4.16	0.92
Cascaded loop control and role of inner loop on robustness	3.66	1.06
Trade-off between control bandwidth and force sensing resolution	4.13	0.86
Small and large force bandwidth	4.11	0.86

Q5: Please rate the usefulness of the following aspects of HandsOn-SEA.

	Mean = 3.91	σ^2 = 0.96
Integrated force sensor	3.94	0.93
No required experience with real-time programming	3.54	1.04
Ability to change controller gains and sensor stiffness	4.12	0.89
Velocity estimation in hardware	3.74	1.03
Integration with Matlab/Simulink	4.21	0.93
Implemented cascaded controller	3.89	0.96

Questions together with their summary statistics are presented in Table III. The Cronbach's α values have been calculated for the each part of the survey; all α values, except for Q3, are evaluated to be greater than 0.7, indicating a high reliability of the survey. It is observed that, due to the increase in the sample size, the reliability of the survey has improved compared to the preliminary results in [4].

A high Cronbach's α is not expected for Q3 as the participants tend to rank their preferences for this question, rather than separately rating each choice. Ranking the choices naturally results in a low Cronbach's α, since a high Cronbach's α is attained when the variance of answers to the same question is low and the variance between the total points is high.

The main results of the survey can be summarized as follows:

- Responses to Q1 indicate that knowledge of dynamic systems and controls theory is essential, while some hands-on experience with programming and hardware is useful.
- In Q2, students indicated that they find simple working principle, robustness, and user-friendliness as important aspects.
- Responses to Q3 indicate that students evaluated the modules to be useful for mechatronics students and robotics researchers.
- Answers to Q4 provide evidence that students evaluate the modules effective in helping them learn fundamental concepts and trade-offs in robotics. In particular, the mean scores averaged over all concepts indicate that students *agreed* that HandsOn-

SEA helped them understand concepts in general, while the mean scores for individual concepts show that proposed modules were perceived as effective for teaching each of these concepts.

- For Q5, the mean scores of individual features indicate that students *appreciated* the fact that HANDSON-SEA provides them with integrated force and velocity sensing, a simple programming interface, and easy-to-use controllers.

B. Effect of HANDSON-SEA on Student Performance

In addition to the survey results that capture students' perceptions and evaluations, we have also studied the course learning outcomes and the effect of HANDSON-SEA on student performance by comparing student final exam grades when the course has been taught with and without utilizing HANDSON-SEA.

Following questions that require a high degree of knowledge synthesis according to SOLO taxonomy were asked in the final exams: *"Explain sensor actuator non-collocation and why it detrimentally impacts the controller performance. Discuss why explicit force control systems inherently possess sensor actuator non-collocation."*

The student performances on this final exam question for the five semesters were compared. Figure 2 presents the distribution of grades per semester, verifying the consistency and close to normal distribution of grades for different semesters. A one-way ANOVA was conducted to determine the significance of HANDSON-SEA on the quantitative final exam question grades over different semesters. ANOVA results indicate that the effect of the semester is significant with $F(4, 124) = 5.48$, $p < 0.0004$. Tukey's honestly significant difference procedure was employed for multi-comparisons, as it is known to be a conservative method for one-way ANOVA with different sample sizes. Multi-comparisons results indicate that student performance in Spring 2015 when HANDSON-SEA was not used is significantly worse than all other terms when HANDSON-SEA was used. In particular, in Spring 2015, students scores have a mean of 29.3% with a 6.21% standard deviation, while the mean has significantly increased to 66.1% with an 11.3% standard deviation in Spring 2016, to 64.5% with a 7.67% standard deviation in Fall 2016, to 70.6% with a 10.2% standard deviation in Fall 2017, and 61.8% with a 9.67% standard deviation in Fall 2018, respectively. The effect size is significant as the scores have more than doubled with the introduction of HANDSON-SEA to the laboratory curriculum.

The achievement of course learning outcomes for the laboratory sessions (introduced to the course evaluations with the Spring 2016 updates) is reported in Table IV as a second metric. On average more than 70% of students displayed satisfactory or better competence on CLO-1 and CLO-2, indicating high success of the instructional design of the laboratory sessions with HANDSON-SEA.

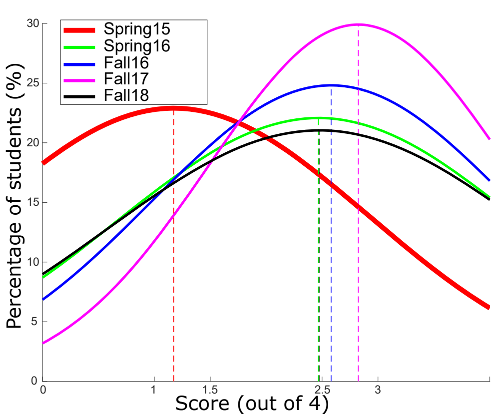

Fig. 2: Distribution of exam grades per semester

TABLE IV: Achievement of Laboratory Session Learning Outcomes

Term	Total # of students	# successful at CLO-1	% successful at CLO-1	# successful at CLO-2	% successful at CLO-2
Spring 2016	15	11	73%	11	73%
Fall 2016	31	22	71%	23	74%
Fall 2017	17	13	76%	12	71%
Fall 2018	28	20	71%	21	75%

To rule out the effects of external variables as much as possible, we note that students are admitted to Sabanci University based on academic merit, through a nationwide centralized exam and the performance of the student population does not vary significantly among the classes of 2015, 2016, 2017 and 2018, as evidenced by overall student performance metrics carefully monitored by the university. The *Introduction to Robotics* has been delivered by the same instructor since 2012, course materials have already been fully developed by Spring 2015, and no fundamental changes (other than the introduction of laboratory sessions with HANDSON-SEA in Spring 2016) has been introduced since then. The teaching performance monitored though standard teaching evaluations administered by Sabanci University rectorate remained consistent throughout Spring 2015–Fall 2018. Furthermore, students taking the course were assigned a sample exam that provided comprehensive a list of the fundamental concepts that are essential in the study of robotic systems.

While the ordering effect cannot be completely eliminated, as it would not be fair to students who are not provided with the opportunity of experiencing the laboratory assignments, a closer analysis of last four semesters with HANDSON-SEA shows that student performance did not change significantly during this period, indicating the change in performance can be most likely be attributed to the laboratory assignments with HANDSON-SEA.

VII. DISCUSSION AND CONCLUSION

HANDSON-SEA has been systematically evaluated in a senior level robotics course and shown to be effective in teaching some of the fundamental concepts in robotics. High success rate of CLOs indicate that instructional design of the laboratory sessions are effective. Furthermore, the statistically significant increase in student final exam scores with a meaningful effect size indicate that laboratory modules with HANDSON-SEA are beneficial and can help students learn and retain theoretical core concepts more effectively.

In [2], [7] anecdotal case studies, qualitative surveys, and instructor experiences have been provided to show perceived value of haptic paddle devices. It has been argued that haptic paddles improve student enthusiasm, enable hands-on experience, and help materialize abstract concepts. Our results are in good agreement with these experiences.

In [6], the effect of a cohesive set of laboratory exercises with haptic paddles on student understanding of engineering concepts with respect to traditional disjoint labs was studied over two semesters. While a formal analysis is lacking, trends based on grading rubics indicated that important gains in student understanding can be achieved with a cohesive set of laboratory exercises. In [12], a formal analysis was conducted over two semesters to investigate the effect of inclusion of reflective learning activities to laboratory sessions, and a statistically significant performance increase on the overall laboratory grades has been demonstrated. Similar to [6], we compared student performance with and without HANDSON-SEA integration over multiple semesters. Our results support the findings in [6] and extends them by providing a statistically significant improvement on the final exam scores, indicating students learned and retained theoretical core concepts more effectively when haptic educational devices were used as a part of cohesive set of laboratory exercises. Similar to [12], our laboratory sessions included pre- and post-lab assignments with discussions and high success rate of CLOs indicate that instructional design of the laboratory sessions were effective. While the introduction of haptic paddles to the laboratory sessions in [12] did not result in statistically significant changes in knowledge transfer measured through exam performance, our study provides such significant results, as exam questions has been included in the design of the study, student performance was compared for with and without HANDSON-SEA integration, resulting in a fundamental change in the laboratory sessions, and the study has been conducted over five semesters to reach to a sufficiently large sample size.

Similar to [8], our study includes a formal assessment of student learning due to haptic paddle integration conducted over multiple semesters and provide statistically significant difference with a large effect size between student scores. Unlike [8], our study did not aim to determine the timing of learning, but it included a control group to which the course has been delivered without the integration of the haptic paddle. Our results are also in good agreement with [8], as the laboratory sessions significantly improved student performance.

Overall, this study complements other studies in that, formal evaluations over multiple semesters have been conducted to compare student performance with a control group to which the course has been delivered without the integration of HANDSON-SEA and statistically significant effects on student performance has been provided as an evidence of student learning, under the fundamental assumption that performance is a good proxy of learning.

The instructor experiences of teaching the course with and without laboratory assignments utilizing HANDSON-SEA also strongly indicate that, instilling in physical intuition, HANDSON-SEA is helpful to support higher-order learning of students. In particular, before the laboratory assignments with HANDSON-SEA, it has been challenging to achieve a solid understanding by students about the synergistic nature of the plant and the controller dynamics on the robotic system performance, and the fundamental limitations introduced by feedback control. After the lectures have been supported by laboratory exercises utilizing HANDSON-SEA, the interdependent nature of the plant and the controller dynamics can easily be demonstrated by changing the physical stiffness of the device, while a fundamental limitation of feedback control can be discussed through the stability bounds under non-collocation.

During the pandemic, low cost design of HANDSON-SEA has been useful to enable online laboratory sessions by sending a device to each registered student. HANDSON-SEA has also been utilized in the graduate level *Force Control and Bilateral Teleoperation* course at Sabanci University for multiple semesters. Furthermore, HANDSON-SEA has been instrumental in promoting students to work on force controlled robotic applications for their graduation projects, by removing the high cost hardware barrier for developing devices with high force output capabilities and speeding up the project development process. HANDSON-SEA provides a rich platform for design courses, as it possesses many modifiable features along with a simple and robust design that allow students to experience all the design stages, namely determination of design criteria, mathematical modeling, mechatronics design, instrumentation and implementation. To date, over 24 students have completed their graduation projects using HANDSON-SEA and implemented various force-feedback devices with significant impact on technology development, including a haptic pedal feel platform for driving under regenerative braking [29].

Overall, HANDSON-SEA is an open-source force-feedback educational robot that has the potential to be beneficial for the education of a diverse set of concepts in haptics and robotics communities.

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