Hands-On Learning with a Series Elastic Educational Robot

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Abstract. For gaining proficiency in physical human-robot interaction (pHRI), it is crucial for engineering students to be provided with the opportunity to physically interact with and gain hands-on experience on design and control of force-feedback robotic devices. We present a single degree of freedom educational robot that features series elastic actuation and relies on closed loop force control to achieve the desired level of safety and transparency during physical interactions. The proposed device complements the existing impedance-type Haptic Paddle designs by demonstrating the challenges involved in the synergistic design and control of admittance-type devices. We present integration of this device into pHRI education, by providing guidelines for the use of the device to allow students to experience the performance trade-offs inherent in force control systems, due to the non-collocation between the force sensor and the actuator. These exercises enable students to modify the mechanical design in addition to the controllers, by assigning different levels of stiffness values to the compliant element, and characterize the effects of these design choices on the closed-loop force control performance of the device. We also report initial evaluations of the efficacy of the device for pHRI studies.

Keywords: Physical human robot interaction · Series elastic actuation · Educational robots · Force control

1 Introduction

Applications in many areas, including surgical, assistive and rehabilitation robotics, service robotics, haptics and teleoperation aim at establishing safe and natural physical human-robot interactions (pHRI). As applications of pHRI become more widespread, engineers with a thorough understanding of such interactions are necessitated. For gaining proficiency in pHRI, it is important for engineering students to be provided with the opportunity to gain hands-on experience about the synergistic design and control of force-feedback robotic devices.

Hands-on experience has been shown to be crucial in strengthening the understanding of basic engineering concepts [3,5]. Haptic Paddles [12]–single degree-of-freedom (DoF) force-feedback devices–have been successfully utilized as teaching platforms for various system dynamics and controls classes in many

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universities around the world [14]. 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 of these devices, while robustness and low cost enable their availability for large groups of students.

We present HandsOn-SEA—a single DoF educational robot with series elastic actuation (SEA)—and detail its integration to pHRI education, by providing guidelines for the educational use of the device to demonstrate the synergistic nature of mechanical design and control of force feedback devices. In particular, we propose an admittance-type device that relies on closed loop force control to achieve the desired level of safety and transparency during physical interactions and that complements the existing impedance-type Haptic Paddle designs. We also propose and evaluate efficacy of a set of laboratory assignments with the device that allow students to experience the performance trade-offs inherent in force control systems. These exercises require students to modify the mechanical design in addition to the controller of the educational device by assigning different levels of stiffness values to its compliant element, deliberately introduced between the actuator and the handle, and characterize the effects of these design choices on the closed-loop force control performance of the device.

2 Educational Force-Feedback Devices and Their Integration to Engineering Education

Several open-hardware designs concerning force-feedback robotic devices exist in the literature. A pioneering force feedback robot designed for educational purposes is the Haptic Paddle [12]. Haptic Paddle is a single DoF impedance-type force-feedback device that features passive backdrivability and excellent transparency, thanks to its low apparent inertia and negligible power transmission losses. The success of this design has lead to several different versions of the Haptic Paddle [2,6–8,11,15].

Haptic Paddles have been widely adopted to engineering curriculum in many universities [14]. The first investigation of a Haptic Paddle type device in classroom/laboratory environment is conducted in [12]. In this work, Haptic Paddle is proposed to support the learning process of students who have dominant haptic cognitive learning styles. The device is used for an undergraduate course for a semester at Stanford University. The laboratory exercises include 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 educational effectiveness of the Haptic Paddle is measured by a student survey and it has been observed that the students benefited from the device, as it helped them to better grasp engineering concepts.

At the University of Michigan, force-feedback devices iTouch and the Box are used in engineering undergraduate courses [7]. In a mechanical engineering course, the device is used to support the learning of students about concepts such as frequency domain representations, dynamical system modeling and haptic interactions. In the laboratory sessions, students implement virtual mass, spring, damper dynamics using an analog computer, experimentally verify the resonant frequency of the device and compare it with the theoretical predictions. In an electrical engineering course, students are introduced to integrating sensors and actuators to micro-controllers, learned about hybrid dynamical systems and improved their programming skills. Students also decode quadrature encoders, perform I/O operations and code CPU interrupts. Moreover, virtual wall and virtual pong game implementations are performed.

Haptic Paddle is also used in an undergraduate system dynamics course at Rice University [2]. The use of the device aims to improve the effectiveness of the laboratory sessions and introduce students to haptic systems, where virtual environments can be used to assist the learning process of complex dynamics phenomenon. Motor spin down tests, system component measurements, motor constant determination, sensor calibration and open- and closed-loop impedance control experiments are performed as a part of the laboratory exercises.

A systematic analysis of integrating Haptic Paddle in an undergraduate level pHRI course is conducted in [6]. The pHRI course covers 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 include implementation of open-loop and close-loop impedance controllers, gravity and friction compensation methods, and admittance controllers. Moreover, students are asked to complete course projects that combine the concepts the learned throughout the lectures. The effectiveness of the Haptic Paddle based instruction is measured by student surveys, using Structure of Observed Learning Outcomes method. It has been observed that hands-on learning is beneficial for pHRI and laboratory sessions can help students learn theoretical concepts more efficiently. Furthermore, students' evaluation of the device is positive, while instructors observe improved success rate in their exams.

Haptic Paddle is also used in an undergraduate system dynamics course at Vanderbilt University [8]. The laboratory sessions include analyzing first and second order system models, determining equivalent mass, damping and stiffness of these system, 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. The efficacy of Haptic Paddle integration to the course is measured by student surveys and it has been observed that when the device is used as a part of the course, the students have higher cumulative scores and better retention rates for the concepts they learned throughout the course.

Recently, the latest version of Stanford Haptic Paddle, called Hapkit, has been integrated as the main experimental setup in a massive open online course (MOOC) offered and made easily accessible all around the world [11].

As an admittance-type device, HandsOn-SEA complements all of these existing Haptic Paddle designs by enabling students to experience admittance control architectures for pHRI, and by demonstrating the design challenges involved in the mechatronic design of such robotic devices.

3 HandsOn-SEA

3.1 Design

HandsOn-SEA is designed to be compatible with existing Haptic Paddle designs, such that existing devices can be equipped with SEA with minimal modifications. To achieve this goal, the sector pulley, common to almost all Haptic Paddle designs, has been modified to feature a compliant element and a position sensor to measure deflections of this compliant element. In particular, the monolithic rigid sector pulley-handle structure is 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 (as in original Haptic Paddle designs), and the sector pulley is attached to the handle through a cross-flexure pivot, a robust and simple *compliant* revolute joint with a large range of deflection [9,10,18]. The center of rotation of cross-flexure pivot is aligned with the rotation axis of the handle (the ball bearing), while the Hall-effect sensor is constrained to move between the neodymium block magnets embedded in the sector pulley. Figure 1(a)–(c) present HandsOn-SEA and its solid model, together with a finite element model of the proposed compliant element under constant torque loading.

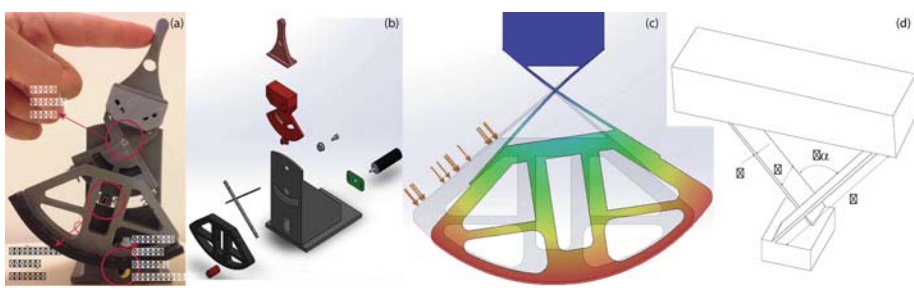

Fig. 1. (a) HandsOn-SEA (b) Exploded CAD model (c) An exaggerated finite element model of the cross flexure pivot and (d) Geometric parameters governing its stiffness

As in other designs, the sector pulley of HandsOn-SEA can be actuated by capstan drive or friction drive transmission. In our current prototype, we have preferred 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 can significantly decrease the rendering performance of Haptic

Paddle devices under open-loop impedance control [15], these parasitic effects due to low quality power transmission elements can be effectively compensated by the robust inner motion control loop and aggressive force feedback controllers of the cascaded control architecture of SEA [19]. Our current design employs a ($25) surplus geared coreless DC motor with a gearhead and an encoder.

Figure 1(d) presents a schematic model of the cross-flexure pivot. Five parameters govern the deflection and stiffness properties of 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 [9,10].

Unlike the original Haptic Paddle designs, HandsOn-SEA necessitates two position sensors: one for measuring the motor rotations and the other one for measuring the deflections imposed on its elastic element. Since our surplus motor already 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 the low cost ($2.5) Hall-effect sensor is proper for measuring these deflections, since the required range for measurements is small, resulting in robust performance of these sensors.

A low cost PWM voltage amplifier ($3.75 TI DRV8801 H-bridge motor driver with carrier) is used to drive the DC motor. Unlike the impedance-type Haptic Paddle designs, this selection is not a compromise solution for HandsOn-SEA, that trades-off performance for low cost. On the contrary, PWM voltage amplifier is a natural choice for cascaded loop SEA control (see Fig. 6), since the velocity (not the torque) of the motor is controlled by the fast inner motion control loop and any high frequency vibrations (due to PWM switching) are mechanically low-pass filtered by the compliant element before reaching to the user's hand.

We have implemented controllers for the SEA robot using a low-cost ($25) TI LaunchpadXL-F28069M micro-controller, since this cost effective industrial grade controller can decode quadrature encoders and estimate velocities from encoder measurements on hardware. Furthermore, this micro-controller can be programmed through the Matlab/Simulink graphical interface and allows for implementation of multi-rate control architectures with real-time performance.

3.2 Dynamic Model

The series elastic robot can be modeled as a single link manipulator actuated by a DC motor. Figure 2 and Table 1 provide the relevant parameters for dynamical modeling.

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 smaller than its mechanical time constant (5.31 ms), the transfer function from

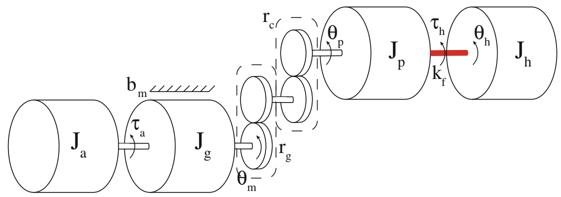

Fig. 2. Dynamic model of HandsOn-SEA

Table 1. Parameters

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

motor voltage $V(s)$ to motor velocity $s\theta_m(s)$ can be derived as

$$\frac{s\theta_m(s)}{V(s)} = \frac{K_m/R}{Js+b} \quad (1)$$

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 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

$$\frac{s\theta_m(s)}{\tau_h(s)} = \frac{-1/(r_g r_c)}{Js+b} \quad (2)$$

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.

4 Performance Characterization

We have characterized the control performance of the series elastic robot through a set of experiments. Since the performance of the cascaded control architecture

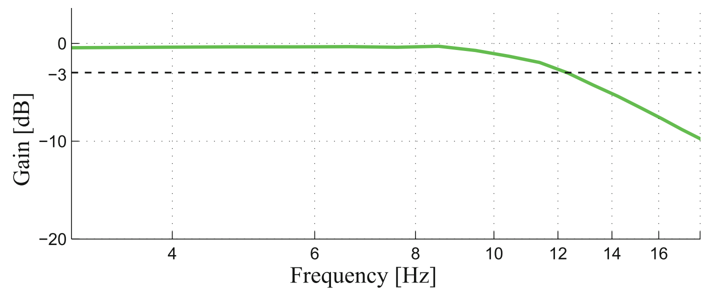

Fig. 3. Velocity control bandwidth

for SEA highly relies on the performance of the inner motion control loop, first, we characterize the velocity bandwidth of the device.

Figure 3 presents the magnitude Bode plot characterizing the velocity bandwidth as 12 Hz. Indeed, up to this frequency the robot can be regarded as a perfect velocity source as necessitated by the outer force and impedance control loops. Given the bandwidth limitations of human motion, 12 Hz is evaluated to be adequate for an educational robot. Furthermore, this bandwidth can easily be increased by properly modifying the capstan and/or gear transmission ratio used in the system.

We have also characterized the force control bandwidths of HandsOn-SEA under cascaded control architecture. Figure 4 depicts Bode magnitude response plots of the device under closed-loop force control for tracking small, medium and high force references.

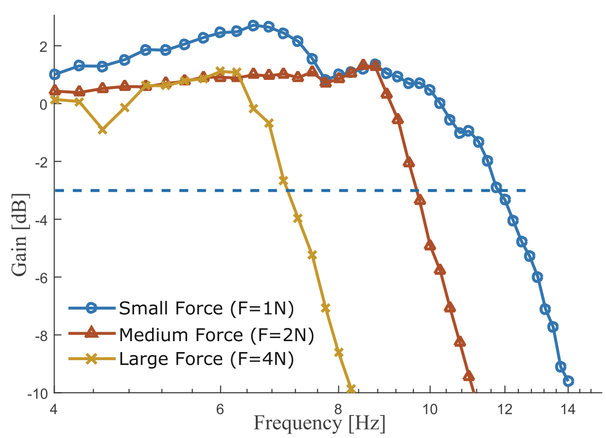

Fig. 4. Bode magnitude plots characterizing small, medium, and high force bandwidths

As expected, the small force (1N) bandwidth of the system is identical to its velocity bandwidth. The medium (2N) and high (4N) force bandwidths of the system are lower, since the actuator speed saturates as the forces get higher.

Thanks to use of geared motors in addition to the sector pulley, the force output of the current prototype is 3–5 times higher than Haptic Paddles. While the low force control bandwidth of HandsOn-SEA is as wide as the force bandwidths reported in [2,6], the control bandwidth decreases as larger forces are commanded. These bandwidths may be improved by increasing the velocity of the system by selecting a faster motor or decreasing the capstan ratio. Furthermore, since medium and high force bandwidths are directly linked to the stiffness of the elastic element of the SEA, they can be increased by stiffening the compliant element, that is, a stiffer cross-flexure pivot can be used to achieve a larger force-control bandwidth during high force tracking tasks.

5 Laboratory Exercise Modules

The performance of explicit force controllers suffers from a fundamental limitation imposed by non-collocation, due to the inevitable compliance between the actuator and the force sensor [1,4]. In particular, non-collocation introduces an upper bound on the loop gain of the closed-loop force-controlled system, above which the system becomes unstable. HandsOn-SEA can be utilized to demonstrate this fundamental limitation of force control and series elastic actuation to students through a set of laboratory modules as follows:

Module 1. This module aims at studying motion control and stability limits of a single DoF rigid-body dynamic system. Students are asked to implement motion control of the DC motor of the device, to which an encoder is attached. Students also analyse the linear second-order rigid-body model of the motor control system and study the stability limits imposed on the position controller gains through a root-locus analysis. Since the root-locus plot of the position-controlled rigid-body model has two asymptotes, no instabilities are expected to take place as the controller gains are increased. The students tune their motion controllers for the DC motor for maximum performance, until practical stability limits are achieved. Bandwidth limitation of the actuator, unmodelled dynamics of the device, sampling-hold effects and sensor noise are explained as the underlying reasons for the instability observed at high control gains. To demonstrate the effect of actuator bandwidth on the stability of the motion control system, the actuator input is passed though a first order low-pass filter and the effect of such filtering on the root-locus plot is demonstrated. After tuning the motion controller, the students are asked to characterize the velocity bandwidth of the DC motor as a part of this assignment.

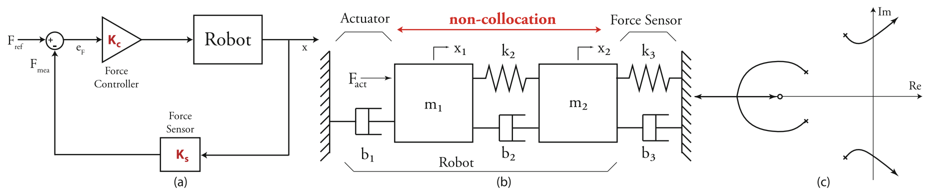

Fig. 5. (a) Explicit force controller (b) Linear dynamic model capturing the non-collocation between the sensor and the actuator (c) Representative root-locus plot non-collocated system under explicit force control

Module 2. This module aims to demonstrate the inherent instability of systems that have sensor actuator non-collocation. Students are asked to perform explicit force control based on the force estimations acquired through the deflections of the cross flexure pivot, as depicted in Fig. 5(a). When students implement this controller, they experience that the control gains need to be kept low, not to induce instability and chatter during contact tasks. This phenomena is attributed to the non-collocation between the force sensor and the motor that drives the system and students are asked to model this non-collocation by a simple linear model that captures the first vibration mode of the system, as presented in Fig. 5(b). Students derive the underlying dynamic equations of the system to verify that the compliance between the sensor and the actuator introduces two poles and a singe zero to the earlier rigid-body model, adding a third asymptote to the root-locus plot, as presented in Fig. 5(c). Students are also asked to analyse two other linear models, where compliance is introduced only to the robot base or to the environment, to discover that both of these models add the same number of poles and zeros to the system. By completing this module, students are expected to convince themselves that the instability is mainly due to the non-collocation between the sensor and the actuator.

Module 3. This module aims to provide students with an intuitive understanding of the trade-off between the sensor stiffness and the force controller gain. Students use several different series elastic capstan modules, each possessing different levels of compliance. Students are asked to characterize the stiffness of the sensor based on the analytical model of the cross flexure pivot and experimentally determine the highest stable explicit force controller gain that can be implemented for each level of compliance. The students are expected to observe that the more the force sensor stiffness is decreased, the more the force controller gains can be increased, without inducing instability or chatter.

Module 4. This module aims to introduce and provide hands-on experience with SEA. First, the underlying idea of SEA is explained as the reallocation of limited loop gain of the system with noncollocated sensor and actuator, to decrease the force sensor stiffness such that the force controller gain can be increased. It is emphasized that more aggressive force-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. Then, the bandwidth limitation of the resulting force controlled system, due to the introduction of the compliant sensing element is discussed. Output impedance characteristics of SEA is studied, emphasizing active backdrivability of the system within the force control bandwidth and limited apparent impedance of the system for the frequencies over the control bandwidth, due to inherent compliance of the force sensing element. Low pass filtering behavior of the system against impacts, impulsive loads and high frequency disturbances (such as torque ripple) are demonstrated [16]. As a part of this module, students are asked to perform a set of force control experiments with two different levels of joint compliance to experience the trade-off between the force-control bandwidth and force control fidelity of SEA [13].

Module 5. This module introduces the cascaded controller architecture [17,19] for SEA and evaluates the force tracking performance of the device under cascaded control. The cascaded control architecture for SEA is depicted in Fig. 6. The controller consists of an inner velocity control loop and an intermediate force control loop and an outer impedance control loop. 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 adequately designed inner loop. Finally, the outer loop determines the effective output impedance of the system. The controller parameters are selected as suggested in [17] to ensure passivity of interaction.

Module 6. This module aims to demonstrate the performance trade-offs for SEA by letting students characterize the small, medium and high force bandwidth performance of the device.

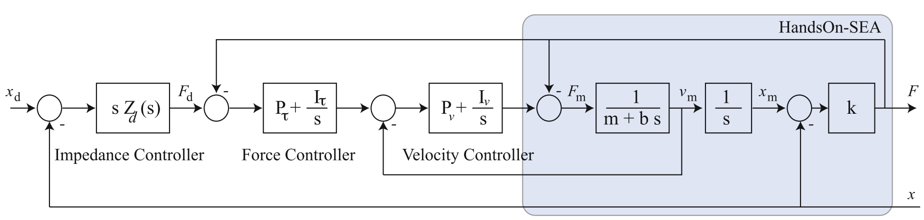

Fig. 6. Cascaded control architecture of HandsOn-SEA

6 Evaluation

We have used HandsOn-SEA for teaching a workshop on force control to 6 undergraduate students (juniors and seniors) and 5 graduate students (MS and PhD) with mechatronics background. All of these students had a background on system dynamics and controls; most of them did not have any background on force control or series elastic actuation. During the workshop, we have implemented Modules 1–6, utilizing the device to demonstrate the concepts. Students were given access to the device to experience the effect of different controller gains, stiffness values and control architectures on force control performance. After the workshop, students filled in a questionable as in Table 2.

The statistical analysis of student responses revealed that the factors of major, background and level were not statistically significant at the 0.05 level; hence, all responses are aggregated for reporting. The Cronbach's α values have been calculated for Q3–Q5 and for the whole survey, and all α values are evaluated to be greater than or equal to 0.7, indicating high reliability of the survey.

The survey includes 5 questions: Q1 is aimed at evaluating the background required by the students, Q2 is for assessing the useability, Q3 is for determination of target population, 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 the five-point Likert scale, ranging from "1" *not at all* to "5" *very strongly* is used to measure agreement level of the participants. Questions together with their summary statistics are presented in Table 2.

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 for the completing the modules.
- From answers to Q2, we can infer that students find HandsOn-SEA user friendly, easy to use and understand.
- Responses to Q3 indicate that students evaluate the modules to be most useful for mechatronics students and robotics researchers, and as not suitable for high schools.
- Answers to Q4 provide strong evidence that modules are effective in helping students learn fundamental concepts/trade-offs in force control. In particular, the mean averaged over all concepts indicate that students *strongly agree* that HandsOn-SEA helped them understand concepts in general, while the mean scores for individual concepts show that proposed modules were also effective for teaching each of these concepts.
- For Q5, the mean scores of individual features indicate that students *strongly appreciate* that HandsOn-SEA provides them with integrated force and velocity sensing, simple programming interface and easy to use controllers.

Table 2. 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		77.3 %
Knowledge on controls theory		86.4 %
Familiarity with hardware-in-the-loop		54.5 %
Experience with real-time controllers		52.3 %
Experience with motor drivers		40.9 %
Experience with integrating sensors		50.0 %
Experience in programming		40.9 %
Q2: Which one of the following aspects of HandsOn-SEA do you find important?		
		Frequency
Easy to use		88.8%
Simple working principle		81.8%
Robust		72.8%
Low cost		95.3%
User friendly		88.8%
Easy to build and maintain		79.5%
Q3: How would you rate the usefulness of HandsOn-SEA for the following groups?		
Cronbach's $\alpha \geq 0.7$	Mean	σ^2
	3.99	1.43
Mechatronics juniors and seniors	4.54	0.35
Mechatronics graduates	4.80	0.17
High school students	2.10	1.21
Robotics researchers	4.00	1.60
Q4: How useful were HandsOn-SEA in helping with the following concepts/trade-offs?		
Cronbach's $\alpha \geq 0.7$	Mean	σ^2
	4.08	0.76
Compliant mechanisms	4.36	0.45
Sensor actuator non-collocation	4.27	1.09
Fundamental limitations of force control—compliance-gain trade-off	4.27	0.22
Admittance control	3.55	1.47
Series elastic actuation	4.45	0.47
Backdrivability and output impedance	4.00	0.67
Cascaded loop control architecture and role of inner loop on robustness	3.73	1.02
Trade-off between control bandwidth and force sensing resolution	4.18	0.36
Small and large force bandwidth	3.90	0.89
Q5: Please rate the usefulness of the following aspects of HandsOn-SEA.		
Cronbach's $\alpha \geq 0.7$	Mean	σ^2
	4.16	0.69
Integrated force sensor	4.00	0.40
No required experience with real-time programming	3.90	1.21
Ability to change controller gains and sensor stiffness	4.55	0.27
Velocity calculation in hardware	4.18	0.56
Integration with Matlab/Simulink	4.73	0.42
Implemented cascaded controller	4.36	0.65

7 Conclusions and Discussions

Complementing the existing impedance-type designs educational robot designs, HandsOn-SEA is evaluated to be effective in demonstrating the fundamental concepts in force control. In particular, in addition to the laboratory exercises proposed in [2,12], the series elastic robot can be used to demonstrate the inherent limitations of explicit force control due to the detrimental effects of sensor actuator non-collocation. By varying the stiffness of the flexure joint and the force control gains, the trade-off induced by the stiffness of the compliant element between the device bandwidth and the force sensing resolution can be studied. Admittance and cascaded control architectures can be implemented.

We are currently evaluating HandsOn-SEA in a senior level Introduction to Robotics and a graduate level Force Control courses. After thorough evaluation of its efficacy, we will make the designs/controllers available for educational use.

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