DESIGN, CONTROL and EVALUATION of EDUCATIONAL DEVICES with SERIES ELASTIC ACTUATION

by

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DESIGN, CONTROL and EVALUATION of
EDUCATIONAL DEVICES
with SERIES ELASTIC ACTUATION

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ABSTRACT

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Ata Otaran

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STEM is a curriculum targeted to be used in all educational levels to support the education of students in four specific disciplines–science, technology, engineering and mathematics–in an interdisciplinary and applied approach. Recently, as computational thinking and strong foundation in computing have been identified as defining features that are likely to strongly shape the future, major research and development efforts have been put together to also promote computing by programs like STEM+C, where "C" further emphasizes computing. STEM+C not only aims to make the topics concerning these fields more understandable and enjoyable, but also to make them more accessible and affordable for every group in the society. STEM+C promotes active learning, in other words, direct involvement of the student in class instead of passively listening, as an essential feature of an ideal learning environment and advocates for the use of technology and hands-on experience for strengthening the understanding of fundamental concepts.

We propose HandsOn-SEA, a low cost, single degree-of-freedom, force-controlled educational robot with series elastic actuation, to enable *physical interactions* with educational tools, helping solidify STEM+C concepts. The novelty of the proposed educational robot design is due to the deliberate introduction of a compliant cross-flexure pivot between the actuator and the handle, whose deflections are measured to estimate interaction forces and to perform closed-loop force control. As an admittance-type robot, HandsOn-SEA relies on a force control loop to achieve the desired level of safety and transparency during physical interactions and complements the existing impedance-type force-feedback educational robot designs. HandsOn-SEA also serves as a building block of more complex, higher degrees of freedom force-feedback robot designs.

HandsOn-SEA is effective in the education of STEM+C concepts, as physical interaction with virtual educational environments not only ensures a higher level of student engagement by adding new bi-directional sensorimotor pathway for active student perception, but also improves student motivation by enabling more engaging and exciting learning experiences. Furthermore, HandsOn-SEA allows for quantitative measurements of student progress and enables visually impaired students to benefit from a larger range of educational tools, by replacing certain visual presentations with haptic feedback. Along these lines, we present the integration of HandsOn-SEA into STEM+C education, by providing guidelines for the use of the device for teaching fundamental concepts in physical human-robot interaction (pHRI) at the undergraduate level and for teaching algorithmic thinking at both the high school and undergraduate levels.

For pHRI education, we provide a set of laboratory modules with HandsOn-SEA to demonstrate the synergistic nature of mechanical design and control of force feedback devices. In particular, we propose and evaluate efficacy of a set of laboratory assignments that 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 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, and characterize the effects of these design choices on the closed-loop force control performance of the device. We have evaluated the efficacy of introducing HandsOn-SEA into engineering education by testing the device in a senior level robotics course and provide evidence that the device is effective in providing experience on admittance control architectures for pHRI and instilling intuition about fundamental trade-offs in the design and control of force-feedback devices.

To promote algorithmic thinking, we propose to use force-feedback educational robotic devices for hands-on teaching of algorithms and present an interactive tool for teaching several sorting and search algorithms with such educational devices. The addition of haptic feedback to teach algorithmic thinking is advantageous as haptic feedback enables an effective means of enforcing pairwise comparisons while ensuring data hiding, a key component in explaining several core concepts while teaching several sorting and search algorithms. Furthermore, physical interactions with virtual learning environments paves the way for more flexible, engaging and exciting learning experiences, surpassing what can be achieved by basic physical elements or applications based on pure visualization. We have evaluated the efficacy of introducing haptic feedback into teaching algorithmic thinking by testing the proposed force-feedback application with several student groups and provide evidence that the approach is effective in instilling the core principle of formulating a precise sequence of instructions for performing sorting tasks, in a technology independent manner.

ÖZETÇE

Uygulamalı Egitim Amaçlı Seri Elastik Eyleyici Tahrikli Eğitim Cihazlarının
Tasarımı ve Denetimi

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STEM, öğrencilerin bilim, teknoloji, mühendislik ve matematik alanlarında alacakları eğitimi her seviyede desteklemek için geliştirilmiş bir müfredattır. Son zamanlarda, bilgisayar bilimi ve algoritmik düşünme eğitiminin geleceği şekillendirecek unsurlar olarak kabul görmektedir ve STEM+C —STEM'in hesaplama(computing) ile birleşimi — gibi programlar ile bu konular teşvik edilmektedir. STEM+C yalnızca içerdiği alanlara dair konuların daha kolay anlaşılır ve eğlenceli bir şekilde sunulmasını değil, verilecek eğitimin her kesimden insanlar için ekonomik ve ulaşılabilir olmasını da amaçlanmaktadır. STEM+C ideal bir eğitim ortamının öğrencinin aktif bir şekilde derse katılımıyla sağlanabileceğini ve temel kavramların teknoloji ve pratik eğitim teknikleriyle desteklenmesini savunmaktadır.

Bu çalışmada, STEM+C konularının daha iyi anlatılabilmesi amacıyla, HandsOn-SEA ismini verdiğimiz, düşük maliyetli, tek serbestlik dereceli, seri elastik eyleyici tahriği ile kuvvet denetimi yapabilen bir eğitim cihazı öneriyoruz. Cihazın özgünlüğü, tutacak ve kasnak bölümleri arasına yerleştirilen çapraz esnek eklem ile sağlanmaktadır. Bu eklemin döner eksende gerçekleştirdiği sapma miktarı ölçülerek tutacak kısmına uygulanan kuvvetler hesaplanıp geri beslenerek kuvvet denetimi yapılmaktadır. HandsOn-SEA, admittans türü bir cihaz olarak, etkileşim sırasında güvenliği ve istenilen seviyede şeffaflığı sağlayabilmek için kapalı çevrim kuvvet denetimi kullanmaktadır ve impedans türü eğitim amaçlı kuvvet denetimi cihazlarını tamamlar niteliktedir. HandsOn-SEA ayrıca daha karmaşık, daha fazla serbestlik dereceli kuvvet geri beslemeli cihazlarının yapı taşı olarak kullanılabilir.

HandsOn-SEA, STEM+C konularını öğretmekte etkilidir. Sanal ortamlarla fiziksel etkileşim, görselliğin dışında ek bir duyusal iletişim yolu oluşturarak ve öğrenim aktivitesinin daha ilgi çekici ve eğlenceli olmasını sağlayarak öğrencinin katılım kalitesini arttırmaktadır. Bunun yanı sıra, HandsOn-SEA, öğrencinin gelişiminin

sayısal olarak ölçülebilmesine ve görsel verileri dokunsal hale getirerek görme engelli öğrencilerinde daha çeşitli eğitim olanaklarından faydalanabilmesine imkan sağlamaktadır. Bu bağlamda, HANDSON-SEA'nın STEM+C eğitimine katılımı için, fiziksel insan-robot etkileşiminin temel kavramlarını ve algoritmik düşünmeyi anlatmakta kullanılmak üzere yönlendirmeler sunuyoruz.

Fiziksel insan-robot etkileşimi eğitimi için kuvvet geri beslemeli cihazların mekanik tasarımlarının ve denetimlerinin sinerjik doğasını anlatmak üzere laboratuvar modülleri sunuyoruz. Bu modüller, özellikle öğrencilerin kuvvet denetimi sistemlerinin başarımlarını etkileyen temel ödünleşimleri laboratuvar çalışmaları ile tecrübe etmelerini sağlamak üzere oluşturulmuş ve öğrenciler tarafından değerlendirilmiştir. Bu deneyler öğrencilerin farklı sertliklere sahip elastik parçalar kullanarak mekanik tasarımla birlikte denetleyiciyi değiştirmelerini ve yaptıkları tasarımsal seçimlerinin kapalı çevrim kuvvet denetimi başarımı üzerindeki etkilerini saptamalarını gerektirmektedir. HANDSON-SEA'nın, insanlarla fiziksel etkileşime giren robot sistemlerinde kullanılan admittans denetimci yapılarının ve kuvvet denetimi sistemlerinde karşılaşılan temel ödünleşimlerin anlaşılmasındaki etkililiği, lisans seviyesinde verilen bir robotik dersinde kullanılarak gösterilmiştir. Benzer şekilde, algoritmik düşünmeyi desteklemek üzere kuvvet geri beslemeli cihazların öğrencilere uygulamalı ve interaktif bir eğitim sunacak şekilde kullanımını öneriyoruz. Dokunsal geri beslemenin, öğrencileri ikili karşılaştırmalara yönlendirirken aynı zamanda bilgi saklamasına imkan vermesi, sıralama ve arama algoritmalarının temel kavramlarının anlatılmasında destek sağlamaktadır. Bunun yanı sıra, sanal öğrenme ortamları ile fiziksel etkileşim; daha esnek, merak uyandıran ve eğlenceli bir tecrübe sunmakta olup, aynı eğitimin fiziksel unsurlar veya sadece görselleştirmeye dayanan uygulamalar ile desteklenmesine göre daha üstün sonuçlar vermektedir. Algoritma eğitiminde, kuvvet denetimli cihazlar aracılığıyla dokunsal geri beslemenin kullanılması öğrenci grupları tarafından değerlendirilmiş ve sıralama problemlerinin çözümü için ihtiyaç duyulan temel bilgileri, teknolojiden bağımsız olarak, anlatmada etkin olduğu görülmüştür.

≪ *Aileme ve dostlarıma* ≫

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Chapter 1

Introduction

STEM is a curriculum targeted to be used in all educational levels to support the education of students in four specific disciplines-science, technology, engineering and mathematics-in an interdisciplinary and applied approach. A great deal of effort and funding is spent on STEM for educating more highly skilled professionals for STEM related careers that will meet requirement of ever expanding technology. These efforts definitely target introduction of more excellent teachers who will be the exercisers and further developers of STEM curricula. A basic method of all STEM based curricula is training by attacking real world technical problems. By this way, students are more motivated about studying, more involved in interactions with others and they get to familiarize with using knowledge in multiple fields together to deal with the interdisciplinary nature of current technology.

Recently, as computational thinking and strong foundation in computing have been identified as defining features that are likely to strongly shape the future, major research and development efforts have been put together to also promote computing by programs like STEM+C, where “C” further emphasizes computing. Computational thinking is regarded as an essential skill not only for computer scientists, but for everyone. Major scientific and engineering efforts involve organizing and processing vast amount of data. Therefore, understanding the role of computation in these fields is comparable in importance to learning about the scientific phenomenon that belong to other STEM fields. The goal of STEM+C is to prevent the notion of treating computers as the black box that are supposed to supply the right result given enough amount of time and support analyzing how their inner workings affect in the overall equation.

STEM+C not only aims to make the topics concerning these fields more understandable and enjoyable, but also to make them more accessible and affordable for every group in the society. STEM+C promotes active learning, in other words, direct involvement of the student in class instead of passively listening, as an essential feature of an ideal learning environment and advocates for the use of technology and hands-on experience for strengthening the understanding of fundamental concepts. STEM+C curriculum students are encouraged to address problems by inventing their own alternative solutions. This helps them better understand the available tool domain, what the advantages and disadvantages of existing solutions are and how to reason the effectiveness of their own solution. Hands-on training in science, engineering or computing, by nature, is based on challenging the students to achieve a goal. Once the students are understand the requirement of the knowledge of the fundamental concepts they are much more motivated to grasp these concepts.

Force feedback educational devices are effective in the education of STEM+C concepts, as physical interaction with virtual educational environments not only ensures a higher level of student engagement by adding new bi-directional sensorimotor pathway for active student perception, but also improves student motivation by enabling more engaging and exciting learning experiences. The ability to physically interact with the learning material helps understand that even if the concept is very abstract, it is basic enough, so that it can be expressed in a tangible way. The amalgam of haptic and visual cues work hand in hand such that they can cover up for each other when one method fall short of conveying the intended information. Furthermore, HandsOn-SEA allows for quantitative measurements of student progress and enables visually impaired students to benefit from a larger range of educational tools, by replacing certain visual presentations with haptic feedback. Along these lines, we present the integration of HandsOn-SEA into STEM+C education, by providing guidelines for the use of the device for teaching fundamental concepts in physical human-robot interaction (pHRI) at the undergraduate level and for teaching algorithmic thinking at both the high school and undergraduate levels.

We propose HandsOn-SEA, a low cost, single degree-of-freedom, force-controlled educational robot with series elastic actuation, to enable physical interactions with educational tools helps solidify STEM+C concepts. We present the integration of HandsOn-SEA into STEM+C education, by providing guidelines for the use of the device for teaching fundamental concepts in physical human-robot interaction (pHRI) at the undergraduate level and for teaching algorithmic thinking at both the high school and undergraduate levels. We have evaluated the efficacy of introducing HandsOn-SEA into STEM+C education by testing the device with several student groups and provide evidence that the device is effective in instilling in intuition about fundamental STEM+C concepts.

1.1 Contributions

We propose HandsOn-SEA, a single DoF educational robot with series elastic actuation (SEA). This educational robot is built to complement the existing Haptic Paddle designs, and differs from them due to its SEA. The novelty of the proposed design is due to the deliberate introduction of a single-DoF compliant cross-flexure pivot between the actuator and the handle, whose deflections are measured to estimate interaction forces and to perform closed-loop force control. Unlike other force-feedback educational robot designs that are of impedance-type, the proposed device is an admittance-type robot with a force sensing element that is integrated to the design and relies on a closed-loop force control to achieve the desired level of safety and transparency during physical interactions. Furthermore, the educational robot is designed to be compatible with existing Haptic Paddle designs, such that these devices can be equipped with SEA by a simple change of their capstan sector with our proposed design.

We also present the integration of HandsOn-SEA into education. For pHRI education, we provide guidelines for the use of the device to demonstrate the synergistic nature of mechanical design and control of force feedback devices. In particular, we 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 due to the non-collocation between the force sensor and the actuator. 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, and characterize the effects of these design choices on the closed-loop force control performance of the device. Finally, we evaluate the efficacy of introducing HandsOn-SEA into engineering education by testing the device in a senior level robotics course and provide evidence that the device is effective in proving experience on admittance control architectures for pHRI and instilling in intuition about fundamental trade-offs in the design and control of force-feedback devices. The results significantly extend the preliminary evaluations reported in [1].

HandsOn-SEA is very suitable for creating interactive environments aimed to teach basic STEM concepts to high school students. There has been great examples of teaching basic physical concepts with Haptic Paddles and their derivatives. To extend the spectrum of K12 subjects that can be taught via HandsOn-SEA with more abstract topics we develop an application to teach students algorithmic thinking. This application aims to create a virtual environment where the students can first understand the necessity of algorithms tackling the challenge that is presented to them. Then they learn about the algorithms and finally practice them in an interactive way. The addition of haptic feedback to teach algorithmic thinking is advantageous as haptic feedback enables an effective means of enforcing pairwise comparisons while ensuring data hiding, a key component in explaining several core concepts while teaching several sorting and search algorithms. The evaluation of the efficacy of this application is presented in this thesis.

The working principle of HandsOn-SEA can be generalized to broader classes of devices that can be used for achieving various tasks. We present a pantograph parallel mechanism and an under-actuated ball beam balancing system which can be used for the education of robotic researchers on the kinematics, controls and sensor fusion topics. The simplistic design of HandsOn-SEA allows modular extensions to be made easily by the addition of several off-shelf and rapidly manufactured parts.

1.2 Outline

The rest of the thesis is organized as follows. Previous works on educational force-feedback robots and series elastic actuation are reviewed in Chapter 2. In Chapter 3, the mechanical design, instrumentation. Following on the design features Chapter 4 modeling and the preferred controller architecture are explained.In Chapter 5 performance characterizations of the proposed educational robot are presented. The use cases for the device, in various levels of education are discussed in Chapter 6. This chapter includes educational modules for a senior level mechatronics course and an educational application designed for teaching algorithmic thinking to K12 level students along with evaluation results for both. In Chapter 7, newer designs along with design improvements for extending the use of HandsOn-SEA are introduced. Finally, Chapter 8 concludes the thesis.

Chapter 2

Literature Review

In this section, we review related works on SEA, educational force-feedback robots and a K12 area that we address with HandsOn-SEA.

2.1 Series Elastic Actuation

The performance of explicit force controllers suffers from inherent limitations imposed by non-collocation, due to the inevitable compliance between the actuator and the force sensor [2, 3]. 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. Given the high stiffness of typical force sensors, the available loop gain of the system needs to be mostly allocated for the force sensing element, limiting the use of high controller gains to achieve fast response times and good robustness properties. Consequently, to provide high fidelity force feedback, explicit force control architectures typically rely on high quality actuators/power transmission elements to avoid hard-to-model effects (such as friction, backlash and torque ripple), since these parasitic effects cannot be compensated by robust controllers based on aggressive force-feedback controller gains.

SEA trades-off force-control bandwidth for fidelity, by using compliant force sensing elements in the explicit force control framework [4]. By decreasing the force sensor stiffness (hence, the system bandwidth), higher force-feedback controller gains can be utilized to achieve responsive and robust force-controllers within the control bandwidth of the system. SEAs also possess favorable output impedance characteristics, allowing them 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 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, that acts as a physical filter against impacts, impulsive loads and high frequency disturbances (such as torque ripple) [5].

In SEA, the orders of magnitude more compliant force sensing elements experience significantly larger deflections (with respect to commercial force sensors) under the interaction forces/torques and these deflections can be measured using regular position sensors, such as optical encoders or Hall Effect sensors. Consequently, large deflections enable implementation of low cost force sensors based on regular position sensors and custom built complaint springs. Furthermore, since the robustness properties of the force controllers enable SEAs to compensate for the parasitic forces, lower cost components can be utilized as actuators/power transmission elements in the implementation of SEAs. Revoking the need for high precision and inevitably expensive force sensors, actuators and transmission elements, the cost of SEA robotic devices can be made significantly (an order of magnitude) lower than force sensor based implementations, as successfully demonstrated by the commercial Baxter robot [6].

The main disadvantage of SEA is its relatively low closed-loop bandwidth, caused by the significant increase of the sensor compliance [4]. The determination of appropriate stiffness of the compliant element is an important aspect of SEA designs, where a compromise solution need to be reached between force control fidelity and closed-loop bandwidth. In particular, higher compliance can increase force sensing resolution, while higher stiffness can improve the control bandwidth of the system. Possible oscillations of the end-effector (especially when SEA is not in contact) and the potential energy storage capability of the elastic element may pose as other possible challenges of SEA designs, depending on the application. Table 2.1 summarizes the change in basic characteristics of a series elastic force controlled system when the stiffness is increased to k times the previous value.

TABLE 2.1: Effect of changing stiffness of the elastic element

Multiplier of stiffness constant	k
Maximum force controller gain	1/k
Force sensing resolution	1/k
Maximum continuous force	k
Force controller bandwidth	$\sqrt{k}$

SEAs are multi-domain systems whose performance synergistically depend on the design of both the plant and the controller. The original SEA controller is based on a single force-control loop, where the actuator is torque controlled based on the deflection feedback from the compliant element [4]. Similarly, a PID controller with feed-forward terms have been used in [7]. A fundamentally different approach based on cascaded control loops have been proposed in [8, 9]. In this approach, a fast inner-loop controls the velocity of the actuator, rendering the system into a "ideal" motion source, while an outer-loop loop controls the interaction force based on the deflection feedback from the compliant element. The cascaded control approach has been adapted in many applications [10–12], since this architecture allows for utilization of well-established robust motion controllers for the inner-loop. Furthermore, it has been shown that the passivity of the cascaded control architecture of SEA can be guaranteed with proper choice of controller gains [13, 14].

2.2 Design of Educational Force-Feedback Devices

Many 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 [15]. The 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. In the original design, a Hall effect sensor is used to sense rotations, while custom built (analog) linear current amplifier is utilized to avoid torque ripple associated with PWM type motor drives. Other important aspects 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 lead to several different versions of the Haptic Paddle [16–20, 22]. Table 2.2 summarizes several important features of these designs. The original Haptic Paddle design relies on a capstan drive that provides sufficient torque transmission ratio with low friction losses, resulting in excellent passive backdrivability. However, maintenance of the capstan transmission after cable stretch, fall-off or break is a tedious tasks, especially for educational setups. 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 [16], while a friction drive transmission has been adapted in [19].

In [17], many improvements have been implemented to increase the design robustness and to decrease the manufacturing costs of Haptic Paddle. Further design iterations have been undertaken in [18, 20, 22], where especially the underlying electronics and

Table 2.2: Several important features of Haptic Paddle designs

Device	Power transmission	Sensor(s)	Motor amplifier	Controller	Reported cost
Stanford Haptic Paddle [15]	Capstan drive	Hall effect sensor	Linear current	PC-based I/O card	$30+D/A+I/O
Michigan iTouch [16]	Direct drive	Optical encoder	Linear current	Analog controller	$20
Rice Haptic Paddle [17]	Capstan drive	Hall effect sensor	Linear current	NI myRio	$50+D/A+I/O
ETHZ Haptic Paddle [18]	Capstan drive	Optical encoder	Linear current	PC-based I/O card	$350+D/A +I/O
Vanderbilt Haptic Paddle [19]	Friction	Magnetoresistive sensor	PWM voltage	Atmel micro-controller	$200
Rice Friction Paddle [20]	Friction drive	Hall effect sensor	PWM voltage	Atmel micro-controller	$50+D/A+I/O
Stanford Hapkit [21]	Capstan drive	Hall effect sensor	PWM voltage	Atmel micro-controller	$50
HandsOn-SEA	SEA with cross-flexure pivot and friction drive	Optical encoder at motor Hall effect for deflection	PWM voltage	TI C2000 micro-controller	$50

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 [16]. A PWM voltage amplifier and an Atmel processor based (Arduino) micro-controller are adapted in [19], trading-off the fast control rates of PC based controllers and torque control performance of linear current amplifiers for more compact and low cost controls/power electronics infrastructure. The most recent iteration of these designs, the Hapkit [22], further customizes the controls/power electronics infrastructure proposed in [19] and adds a force sensitive resistor to the device handle.

Two DoF educational robots based on multiple Haptic Paddles have also been introduced [23, 24]. In particular, SnapticPaddle configures dual capstan driven Haptic Paddles to achieve the kinematics of a 2-DoF joystick [23], while grounded direct drive haptic paddles are utilized to actuate five-bar linkages in cTouch [24]. The cTouch device features a compliant five-bar mechanism for reducing friction/backlash and built-in Hall-effect damping for improved stability.

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 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-feedback fidelity even with open-loop impedance control, that is, without the need for force sensing.

HandsOn-SEA is an admittance-type robotic device; hence, is fundamentally different from and complementary to the existing Haptic Paddle designs. Table 2.3 presents some of the essential differences between admittance and impedance type devices. Comparison is made assuming that both devices use a motor with the same power rating but the admittance type one uses a higher transmission ratio.

Table 2.3: Typical characteristics of admittance and impedance type devices

Device type	Admittance	Impedance
Direct force sensing	Necessary	Not necessary
Output impedance	Low	High
Passive backdrivability	Low	High
Velocity control bandwidth	Low	High
Force control bandwidth	Low	High
Continuous force output at the handle	High	Low

2.3 Evaluation of Educational Force-Feedback Devices

Haptic Paddles have been widely adopted to engineering curriculum in many universities [25]. The first investigation of a Haptic Paddle type device in classroom/laboratory environment is conducted in [15]. 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 [16]. 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 pong game implementations are performed.

Haptic Paddle is also used in an undergraduate system dynamics course at Rice University [17]. 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 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 [18]. 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 [19]. 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.

The 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 [22]. A newer version of Hapkit has recently been used to teach physics in secondary education [21].

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. Preliminary evaluations of HandsOn-SEA is reported in [1].

Table 2.4 summarizes the uses of haptic paddles in engineering education in several universities. Typical system characterization and calibration exercises include motor spin down tests, bifilar pendulum test, motor constant determination and sensor calibrations. Every institution requires the knowledge of building, modeling and programming the system and provides the students the necessary general technical knowledge on these aspects.

Table 2.4: Comparison of Educational use of Haptic Paddles

Institution	Course type	Addressed topics
Stanford University	· Design and control of Haptics systems	· Characterization and calibrations · Impedance control and virtual environment implementations
ETHZ	· Undergraduate pHRI course	· Characterization and calibrations and additionally includes system id of certain parameters. · Advanced control and impedance rendering · Virtual environment performance characterizations: KB and Z-width plots for virtual wall implementation
Rice University	· Undergraduate system dynamics	· Characterization and calibrations · Virtual environment performance characterizations
Vanderbilt University	· Undergraduate system dynamics ·	· Characterization and calibrations · First and second order system models, determining equivalent mass, damping and stiffness of the system.
	· Graduate haptic systems course	· Curriculum is not yet published.
University of Michigan	· Undergraduate system dynamics	· Frequency domain representations, dynamical system modeling and haptic interactions

2.4 Use of Force Feedback Devices For Computing

As computational thinking and strong foundation in computing have been identified as defining features that are likely to shape the future, computer science has been rapidly expanding into K12 education. Major research and development efforts have been put together in programs like STEM-C (Science, Technology, Engineering and Mathematics, including Computing) to promote computing and computational thinking at the high school level. Even though programming has been highly promoted and adapted into K12 curricula, computational thinking — the ability to formulate precisely a sequence of instructions, or a set of rules, for performing a specific task that lies at the intellectual core of computing — has received less attention. Promoting computational thinking ability requires that students are provided with a clear understanding of the fundamental principles and concepts of computer science, including abstraction, logic, algorithms, and data representation. These core principles are technology independent and can be illustrated without relying on computers or programming. Algorithmic thinking is one such key ability that can be developed independently from programming. In fact, earliest known algorithms for factorization and finding square roots have been developed by Babylonians at around 1600 BC. It is emphasized in ACM Computing Curricula 2001 [26] that the understanding of the essential algorithmic models transcends the particular programming languages and should be taught separately to avoid distractions of syntax and other requirements and create a solid foundation. We propose to use force-feedback educational robotic devices (Haptic Paddles) for hands-on teaching of algorithms, mainly to high school students. There exists many educational tools to promote algorithmic thinking, most of which rely highly on visualization of basic algorithms. The addition of haptic feedback for teaching of algorithmic thinking offers several unique advantages: i) haptic feedback enables a more effective means of data hiding, a key component in explaining several core concepts, such as systematic pairwise comparisons during sorting, ii) haptic feedback ensures a higher level of student engagement as it not only adds another pathway to the student perception, but also ensures active physical interactions, and iii) haptic feedback may improve student motivation as physical interaction with virtual environments are interesting. Furthermore, visually impaired students may benefit from replacement of visualization with haptic feedback.

Chapter 3

Design and Implementation of HandsOn-SEA

In this section, we detail the mechanical design, instrumentation and power electronics/control infrastructure of HandsOn-SEA.

3.1 Design Objectives

The main design objectives for HandsOn-SEA are determined as follows:

*A*ffordability: The device should be made of easy to manufacture or low cost off the shelf parts.

*E*ase of use: The working principle of the device and the graphical user interface should be easy to understand and use.

*E*ase of building: Building the device should not require generally inaccessible tools and a serious level of prior manufacturing experience.

*R*obustness: The device should be strong enough to endure extensive use by novice experimenters.

*C*ompatibility with other Haptic Paddles: Using HandsOn-SEA along with other Haptic Paddles would help deliver a more holistic education on force control systems. This also helps to further save cost when one chooses to integrate both Haptic Paddles and HandsOn-SEA in a single course.

*M*odularity: The working principle of HandsOn-SEA should be convenient for generalization to more complex systems. Modular extensions to HandsOn-SEA should enable the use of higher degree of freedom systems which are produced by the addition of several parts.

*P*erformance vs. cost trade-off: The overall performance of the device should be satisfactory for the end user. The stiffness of the flexure joint and the motor used in HandsOn-SEAcan be chosen to optimize both the performance and cost effectiveness properties together for the intended task. In particular the force output of the device should be large enough to be detectable while the cost of the device should not be above 70$.

Overall, we are aiming for a simple and robust device. However, a simple design does not imply that its design process is any less challenging. On the contrary, simpler designs are typically harder to come up with. As Leonardo Da Vinci puts it "Simplicity is the ultimate form of sophistication.". The simplicity and robustness are the most important features for attracting broader audiences.

3.2 Mechanical Design and Power Transmission

The main actuation mechanism and dimensions of the proposed robot have been designed to be compatible with existing Haptic Paddle designs, such that existing devices can be equipped with SEA with minimal modifications. Along these lines, to enable built-in force sensing, the sector pulley that 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 (as in the other Haptic Paddle designs), and the sector pulley is attached to the handle through a cross-flexure pivot. A cross-flexure pivot, formed by crossing two leaf springs symmetrically, is a robust and simple *compliant* revolute joint with a large range of deflection [27–31]. A cross-flexure pivot is preferred as the compliant element of the SEA, since this leaf-type compliant pivot distributes stress over the length of its leaf springs and provides robustness by avoiding stress concentrations that are inherent in notch-type compliant elements. 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 constraint to move between the neodymium block magnets embedded in the sector pulley. Figure 3.1 presents a solid model of the design.

As in other 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 [20], these parasitic effects caused by the low quality power transmission element can be more effectively compensated by the inner robust motion control loop and force feedback of the cascaded control architecture of SEA [8, 9].

Our current design employs a surplus ($25) geared coreless DC motor 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

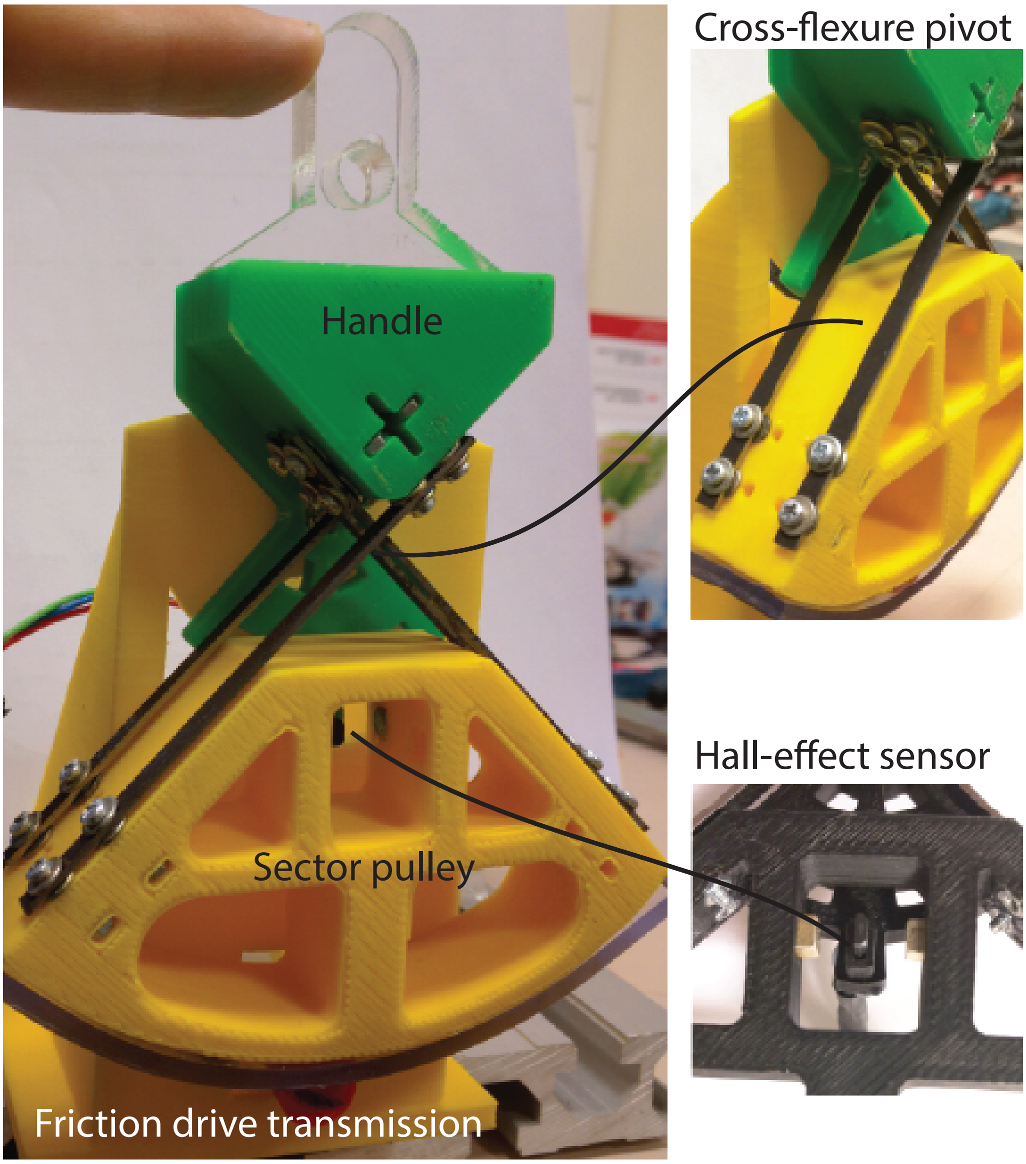


Figure 3.1: HandsOn-SEA – A single DoF series elastic educational robot

and the bearing, can be constructed using additive manufacturing techniques. Please note that the design consists of simple parts that can also be fabricated using other low cost methods, such as laser cutting.

3.3 Sensors and Power Electronics

Unlike the Haptic Paddle designs, HandsOn-SEA necessitates two position sensors: one for measuring the motor rotations and another for measuring the deflections imposed on the elastic element. Since our surplus DC motor 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 the low cost ($2.5) Hall-effect sensor is appropriate for measuring these deflections, since the required range for measurements is small, resulting in robust performance of these sensors. Furthermore, from a pedagogical point of view, this choice enables students to get hands-on experience in integrating both analog (Hall-effect) and digital (magnetic digital encoder) sensors to the control system.

A low cost PWM voltage amplifier ($3.75 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 fast 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.

3.4 Micro-Controller

We have implemented controllers for the series elastic robot using a low-cost $25 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 estimate velocities from encoder measurements on hardware. Furthermore, these micro-controller can be programmed through the Matlab/Simulink graphical interface and Embedded Coder toolbox and allow for easy implementation of multi-rate control architectures with hard real-time performance.

Chapter 4

Modeling and Control of HandsOn-SEA

In this chapter, we detail the dynamic model and controller of the series elastic robot.

4.1 Stiffness of the Cross-Flexure Pivot

Figure 4.1 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 [29, 30]

$$K_\tau = 8(3\lambda^2 - 3\lambda + 1)\frac{EI}{L} \tag{4.1}$$

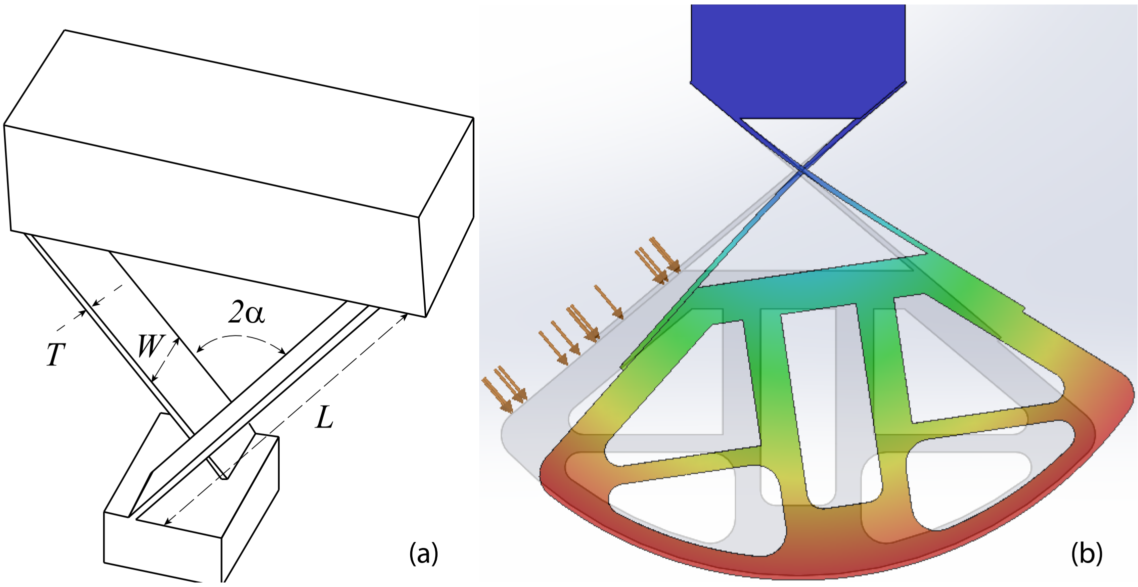


FIGURE 4.1: a) A schematic representation of deflected cross-flexure pivot with parameters governing its deflection and stiffness properties b) An exaggerated finite element model of the proposed compliant element under a constant torque loading

The center shift of the cross-flexure pivot is ignored while calculating these equations to significantly simplify the derivation for the load-rotation relationship. However, given the deflection θ on the spring is small (less than 10°), these equations provide high accuracy, since the δ_x and δ_y components of the center shift δ are of the order of θ^3 and θ^2 respectively, according to [27]. Furthermore, it is shown in [30] that for $\lambda = 87.3\%$, the center shift can be kept minimal.

Figure 4.2 presents two capstans with different stiffness characteristics. The design shown in Figure 4.2(a) features two leaf springs with $\lambda = 0.5$ and possesses lower stiffness. The design shown in Figure 4.2(b) features four leaf springs for better lateral stability and higher stiffness. Furthermore, the dimensionless geometric parameter λ is taken as 87.3% in this design to minimize the center shift of the cross flexure pivot.

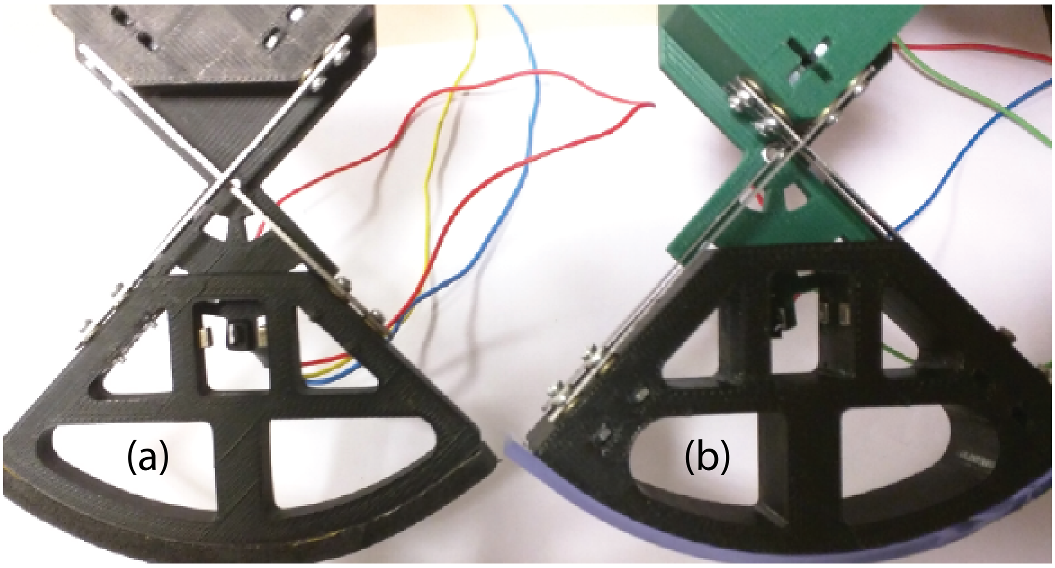


Figure 4.2: Capstans with a) low and b) high stiffness cross flexure pivots

4.2 Dynamic Model

The series elastic robot can be modeled as a single link manipulator actuated by a DC motor. Figure 4.3 and Table 4.1 define and list the parameters that are relevant for dynamical modeling.

The motion of the DC motor is controlled by regulating its voltage. Since the

Table 4.1: 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

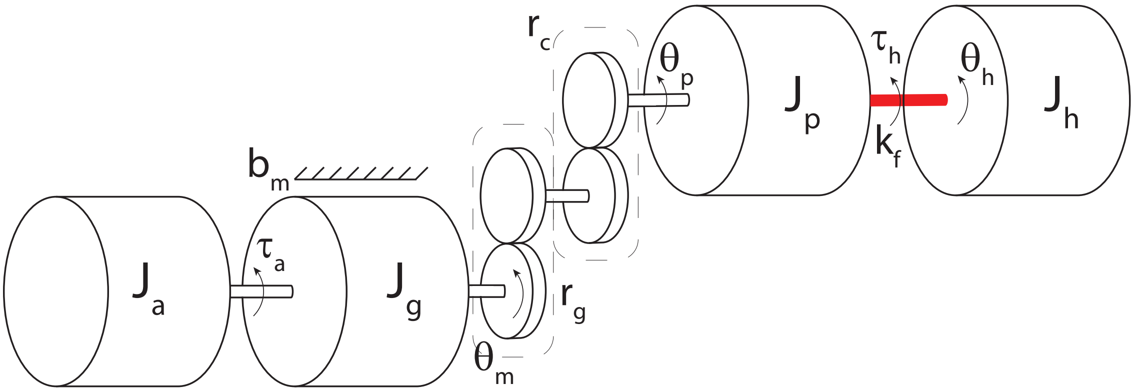


FIGURE 4.3: Dynamic model HANDSON-SEA

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

$$\frac{s\theta_m(s)}{V(s)} = \frac{K_m/R}{Js+b} \tag{4.2}$$

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 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

$$\frac{s\theta_m(s)}{\tau_h(s)} = \frac{-1/(r_g r_c)}{Js+b} \tag{4.3}$$

where the rotation of the pulley is related to the motor rotation by $\theta_p(s) = \theta_m(s)/(r_g r_c)$.

All thw unmodeled dynamics of the system are considered as disturbances that act on the system and is to be compensated by robust motion control of the DC motor.

4.3 Cascaded Loop Controller

Cascaded controllers are implemented for the device as shown in Figure 4.4. The cascaded controller consists of an inner velocity control loop, 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 incorporated 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. For robust operation, the inner loop is run at 10 kHz, while intermediate force and outer impedance controllers are implemented at 1 kHz.

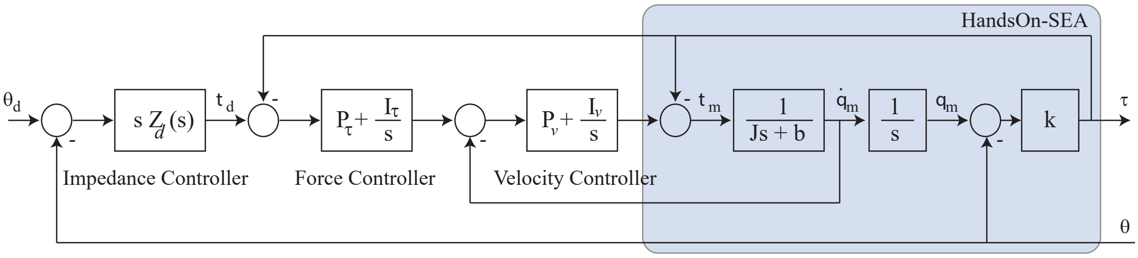


Figure 4.4: Cascaded control architecture

The for the cascaded control architecture the controller parameters can be selected as suggested in [14] to ensure passivity of the interaction.

4.4 Verification of the Hall-Effect Sensor based Force Estimation

We have integrated the Hall-effect sensor to the analog input of the micro-controller board and verified its measurements with respect to a 500 count/inch linear encoder. Figure 4.5(a) presents the experimental setup used for this verification, while Figure 4.6(a) presents sample measurement data from both sensors. The %RMS error between two sensors has been calculated to be lower than 1% for Hall-effect sensor measurements up to ± 3.5 mm, which is chosen as the operating range for the SEA. The magnets placed ± 5 mm apart from the Hall-effect sensor act as hard stops, when larger defections are tried to be imposed.

We have also verified the force estimates of the series elastic element, with respect to a commercial laboratory grade force sensor (ATI Nano17). Figure 4.5(b) presents

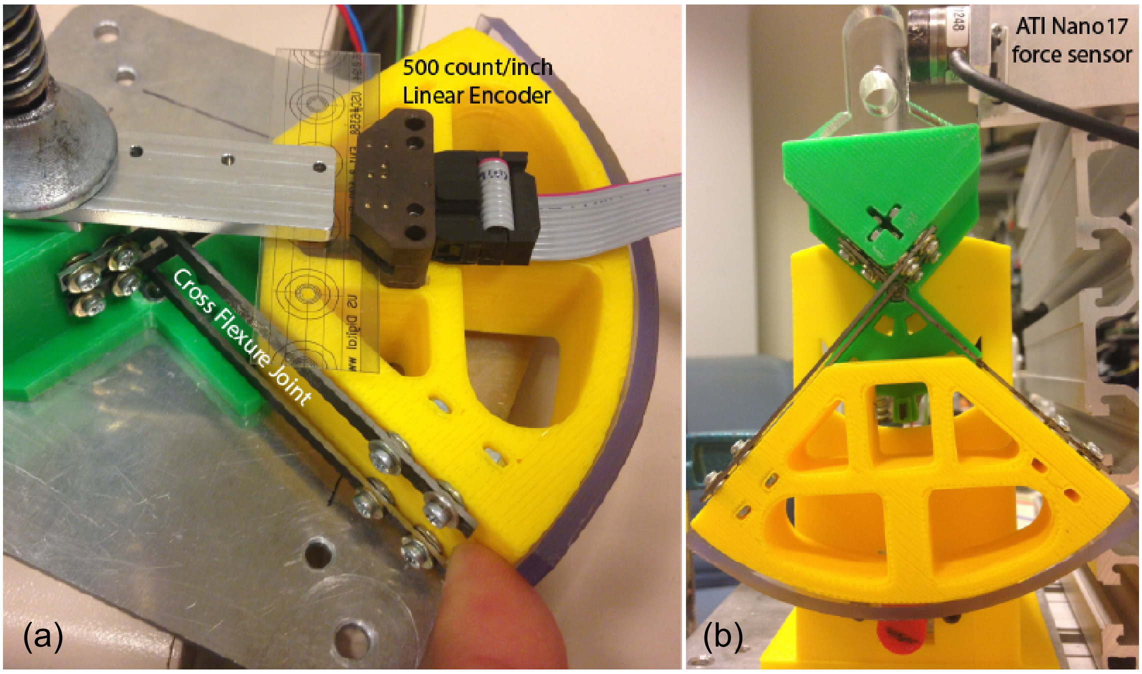


FIGURE 4.5: Experimental set-up used for verification of the a) Hall effect sensor and b) compliant force sensing element

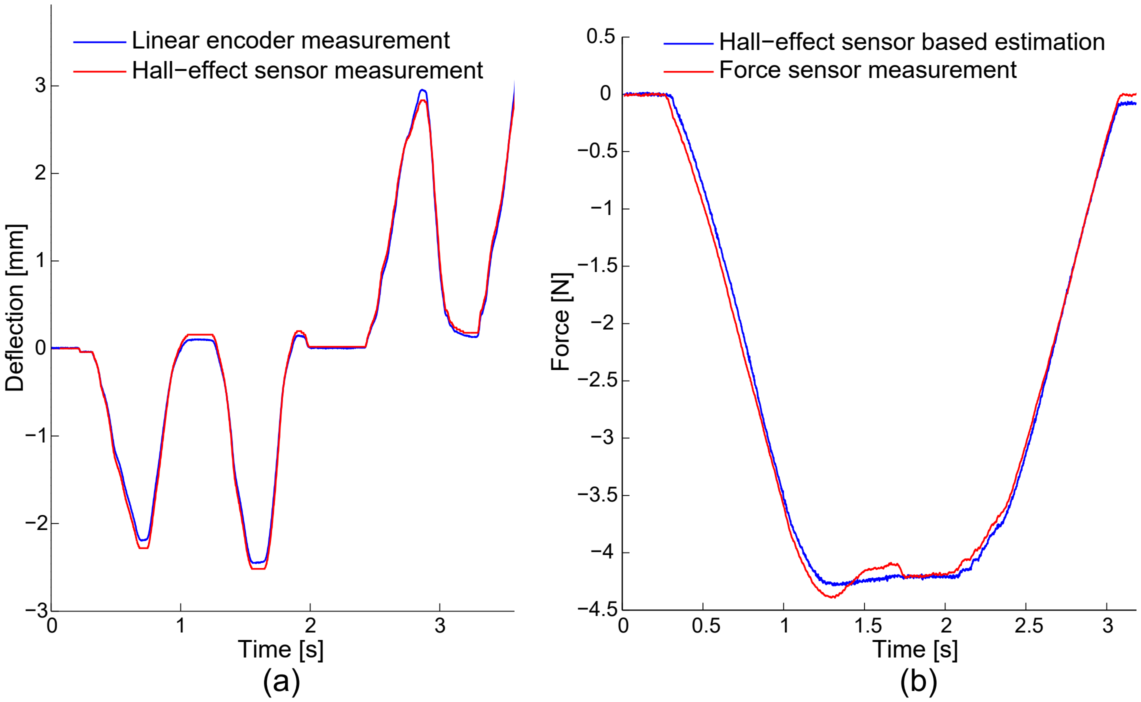


FIGURE 4.6: Experimental verification of a) hall effect sensor measurements and b) force estimates

the experimental setup used for this verification, while Figure 4.6(b) presents sample data/estimates from both sensors. The %RMS error between two sensors has also been calculated to be lower than 5% for Hall-effect sensor measurements within the operating range for the SEA.

Chapter 5

Performance Characterization

We have characterized the control performance of HandsOn-SEA through a set of experiments. This section includes the characterization experiments and their results.

5.1 Velocity Bandwidth

Since the performance of the cascaded control architecture highly relies on the performance of the inner motion control loop, first, we characterize the velocity bandwidth of the device. Figure 5.1 presents the magnitude Bode plot characterizing the velocity bandwidth as 14 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, 14 Hz is evaluated to be adequate for an educational robot; however, for the system this bandwidth can easily be increased by properly adjusting the capstan and/or gear transmission ratio used in the system.

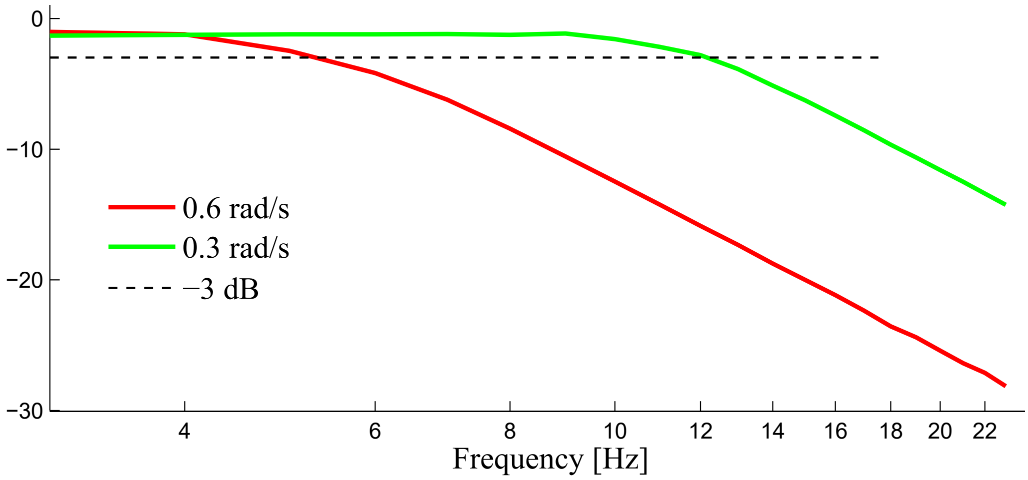


Figure 5.1: Velocity control bandwidth

5.2 Force Control Experiments

Second, we characterized the force control performance of the device. During these experiments, we have attached a force sensor (ATI Nano17) to the system to verify the interaction force estimations of the series elastic element.

5.2.1 Set Point Tracking

The step response of the force control system is presented in Figures 5.2. The set point force control experiments are performed for four reference force values: 0.3 N, 0.6 N, 0.9 N and 1.2 N. The percentage steady state force error for these four references are all calculated to be less than 5%.

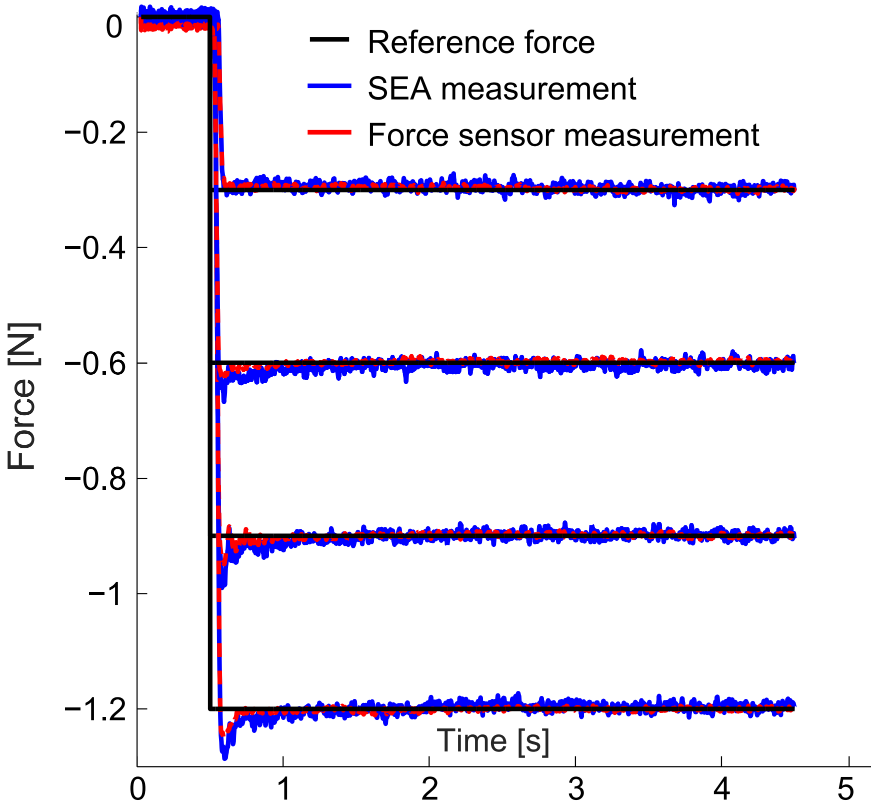


FIGURE 5.2: Set-point force control performance for reference force values of 0.3 N, 0.6 N, 0.9 N and 1.2 N.

5.2.2 Chirp Response

Force tracking performance of the educational robot for a chirp reference signal is given in Figure 5.3. The chirp signal consists of the frequencies up to 3 Hz and has a peak-to-peak amplitude of 0.4 N. The RMS force error between reference force and measured force is characterized as 6.8%, while the error between reference force and estimated force the RMS force error is calculated to be 7.6%.

5.2.3 Force Control Bandwidth

Finally, we have characterized the force control bandwidths of the system. Figure 5.4 depicts Bode magnitude response plots of the device under closed-loop force control.

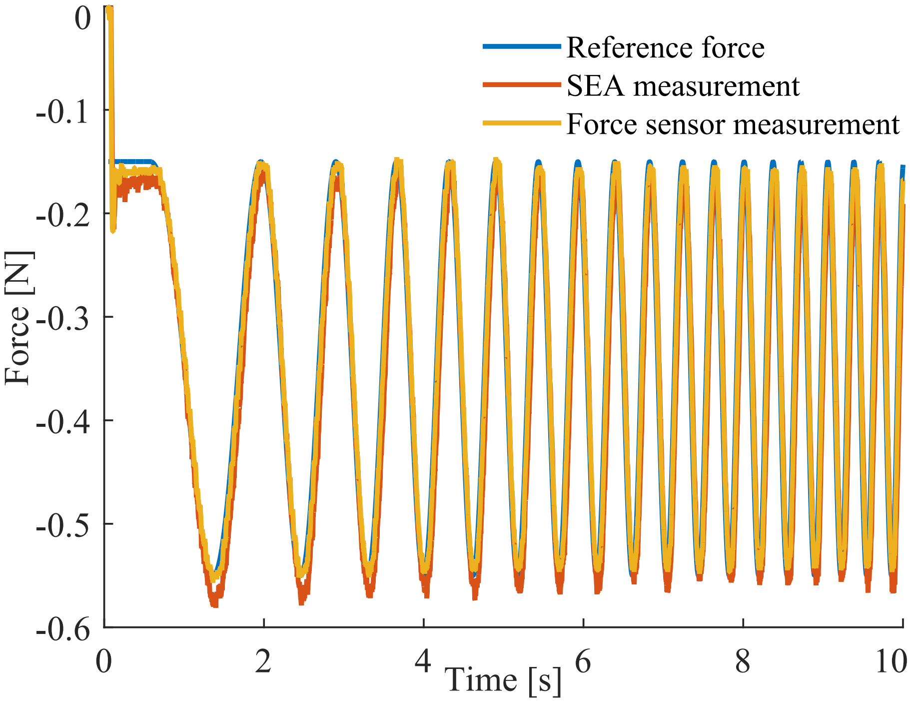


FIGURE 5.3: Chirp force reference tracking performance for frequency range up to 3 Hz.

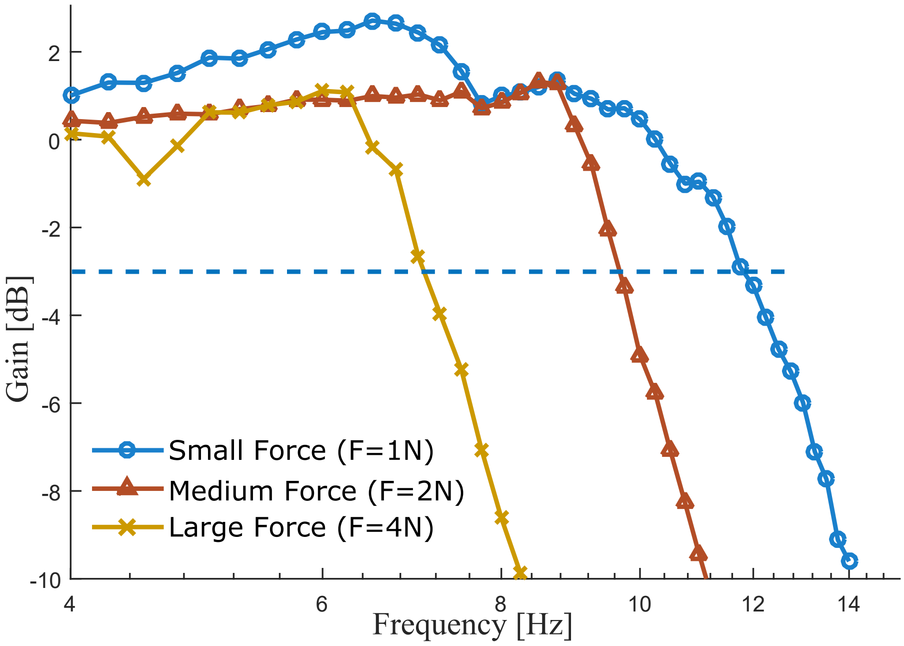


FIGURE 5.4: Bode magnitude plots characterizing closed-loop small, medium, and large force bandwidths

Table 5.1: 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	°
Weight	210	g
Nominal Speed at Gear Output	145	rpm
Velocity Control Bandwidth	14	Hz
Small Force Bandwidth	≈ 12	Hz
Medium Force Bandwidth	≈ 10	Hz
High Force Bandwidth	≈ 7	Hz

As expected, the small force (1 N) bandwidth of the system is close to the velocity bandwidth, while medium (2 N) and high (4 N) force bandwidths of the system are lower, since as the forces get higher, the actuator speed saturates. These bandwidths may be improved by increasing the velocity bandwidth of the system.

Alternatively, medium and high force bandwidths are also directly linked to the stiffness of the elastic element of the SEA, it can be increased by stiffening the compliant element. For instance, for a higher force-control bandwidth, a stiffer cross-flexure pivot as in Figure 4.2(b) can be used.

Table 5.1 summarizes the technical specifications of HandsOn-SEA.

Chapter 6

Educational Use

In this chapter, we first present the educational modules that we have designed to be used in pHRI education for teaching fundamental trade-offs inherent in the design and control of force control systems. In the second section we introduce an interactive application to be used for teaching of algorithmic thinking to K12 level students.

6.1 pHRI Education

This section presents the proposed laboratory modules for pHRI education and the evaluations of the device and the modules, based on student from students who used the device in the laboratory sessions of a senior level robotics course.

6.1.1 Laboratory Exercise Modules

HandsOn-SEA enables students to experience the synergistic coupling between the plant and the controller dynamics on the overall performance of the mechatronic systems. This educational device can be utilized for pHRI studies, to instill in intuition about fundamental trade-offs that exist in the design of admittance-type force-feedback devices.

Complementing the existing impedance-type designs educational robot designs, HandsOn-SEA can be used to demonstrate the inherent limitations of explicit force control due to the detrimental effects of sensor actuator non-collocation, in addition to the laboratory exercises proposed in [15, 17].

In particular, 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 [2, 3]. 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.

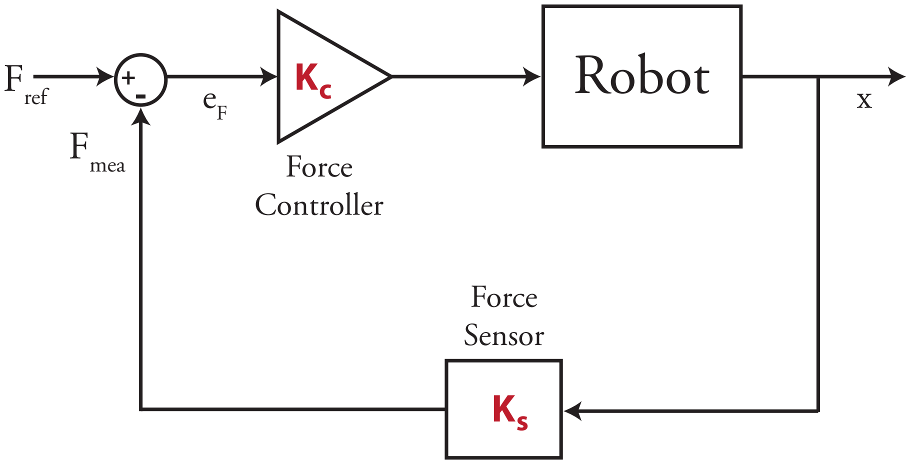


Figure 6.1: Explicit force controller

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 Figure 6.1. 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 Figure 6.2. 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 Figure 6.3. Students are also asked to analyse two other linear models,

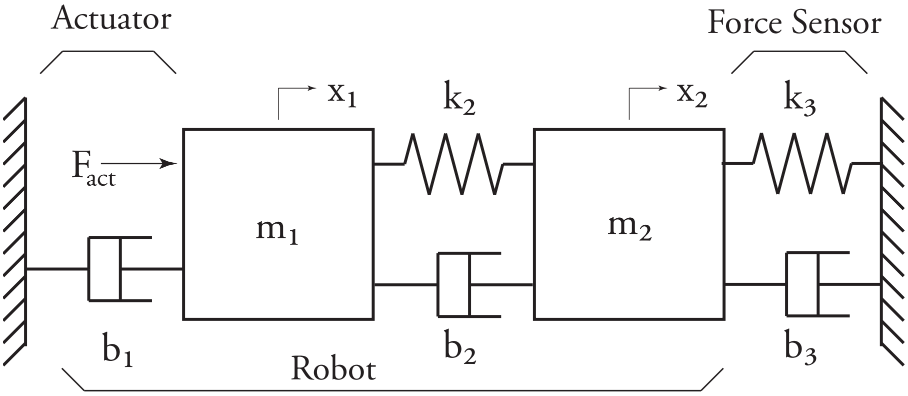


FIGURE 6.2: Linear dynamic model capturing the non-collocation between the sensor and the actuator

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.

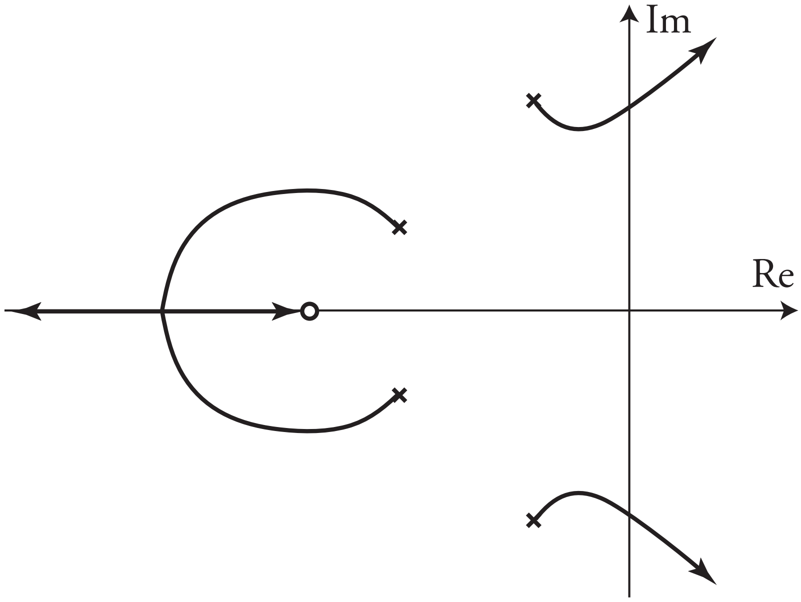


FIGURE 6.3: Representative root-locus plot non-collocated system under explicit force control

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 [5]. 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 [4].

Module 5 This module introduces the cascaded controller architecture [9, 14] for SEA and evaluates the force tracking performance of the device under cascaded control. The cascaded control architecture for SEA is depicted in Figure 4.4. 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.

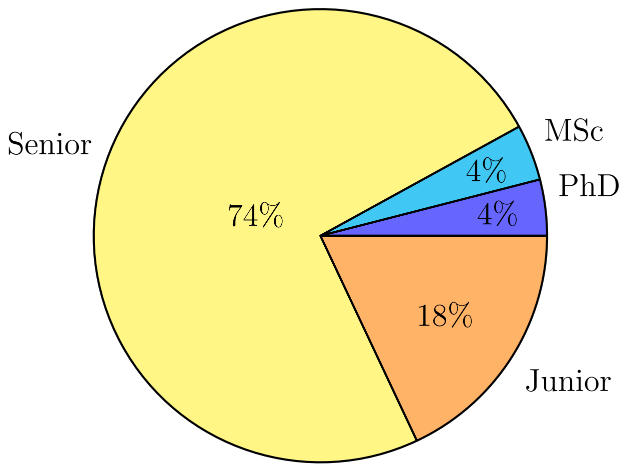
Module 6 This module aims to demonstrate the performance trade-offs for SEA by letting students characterize the small, medium and high force bandwidth performance of the device as presented in Figure 5.4. By completing this module, students are expected to experience the decrease of system bandwidth as force magnitude increases.

6.1.2 Evaluation of Educational Efficacy

Educational effectiveness of HandsOn-SEA and educational modules have been evaluated through student surveys, student performance metrics, and instructor experiences. Furthermore, the ease-of-use and robustness of the device have been tested on general public.

Student Evaluations of HandsOn-SEA We have used HandsOn-SEA for teaching the Introduction to Robotics course at Sabanci University in spring and fall semesters of 2016. The spring semester included 11 senior and 4 junior, 2 MS and

Figure 6.4: Composition of levels of the laboratory session attendees



2 PhD level students whereas the fall semester included 26 senior 5 junior students as represented in Figure 6.4. All of the students had a mechatronics background. As a pre-requisite of the course, all of the students had a background on system dynamics and controls; but none of them had any background on force control or series elastic actuation. During the laboratory sessions of the course, we have implemented Modules 1–6, utilizing HandsOn-SEA. 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 course, students filled in a questionnaire.

The statistical analysis of student responses revealed that the factor of major was not statistically significant at the 0.05 level for any of the survey questions; hence, all responses are aggregated for reporting. The Cronbach's α values have been calculated for the each part of the survey, and except for Q3, all α values are evaluated to be greater than 0.7, indicating high reliability of the survey.

A high Cronbach's α is not expected for Q3. Q3 is composed of relatively more interrelated elements such that most people tend to sort their preferences and rate accordingly. A high Cronbach's α is attained when the variance of answers to the same question is low and the variance of the total points given by each person is high. The sorting tendency results in having a low variance in the total rating resulting in a low Cronbach's α value.

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 6.1.
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 Q2, we can infer that students find HandsOn-SEA user friendly, easy to use and understand.
- Responses to Q3 indicate that students evaluated the modules to be most useful for mechatronics students and robotics researchers, while they evaluated them to be not suitable for high school students.
- 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 scores 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.

Table 6.1: pHRI Educational Modules 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	63.1
Knowledge on controls theory	72.6
Familiarity with hardware-in-the-loop	66.7
Experience with real-time controllers	62.5
Experience with motor drivers	54.2
Experience with integrating sensors	54.2
Experience in programming	53.6

Q2: Which one of the following aspects of HandsOn-SEA do you find important?	Frequency
Easy to use	75.8
Simple working principle	71.6
Robust	69.6
Low cost	83.5
User friendly	74.2
Easy to build and maintain	75.1

Q3: How would you rate the usefulness of HandsOn-SEA for the following groups?	Mean	σ^2
	4.07	1.10
Mechatronics juniors and seniors	4.26	1.04
Mechatronics graduates	4.35	0.90
High school students	3.63	1.30
Robotics researchers	4.04	1.02

Q4: How useful were HandsOn-SEA in helping with the following concepts/trade-offs?	Mean	σ^2
	4.04	0.96
Compliant mechanisms	4.14	1.00
Sensor actuator non-collocation	4.10	0.93
Fundamental limitations of force control—compliance-gain trade-off	4.29	0.86
Admittance control	4.07	0.97
Series elastic actuation	4.00	1.10
Backdrivability and output impedance	4.14	0.87
Cascaded loop control architecture and role of inner loop on robustness	3.60	1.11
Trade-off between control bandwidth and force sensing resolution	4.05	0.88
Small and large force bandwidth	4.02	0.92

Q5: Please rate the usefulness of the following aspects of HandsOn-SEA.	Mean	σ^2
	4.11	0.85
Integrated force sensor	3.83	1.03
No required experience with real-time programming	3.58	1.08
Ability to change controller gains and sensor stiffness	4.05	0.96
Velocity calculation in hardware	3.80	0.99
Integration with Matlab/Simulink	4.00	0.99
Implemented cascaded controller	3.83	0.99

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

Effect of HandsOn-SEA on Student Performance In addition to the survey results that indicate qualitative evaluations of the students, we have also studied the effect of HandsOn-SEA on student performance by comparing student grades when the Introduction to Robotics Course has been taught with and without HandsOn-SEA.

In particular, the same course has been taught in two consecutive years during Spring 2015 and Spring 2016 by the same instructor (last author) with 46 and 15 attendees respectively, while HandsOn-SEA and the laboratory exercise modules have been integrated into the curriculum in Spring 2016. Following question was asked in the final exam of both years:

"Explain sensor-actuator non-collocation and why it detrimentally impacts on controller performance. Discuss why explicit force control systems inherently possess sensor actuator non-collocation."

The student performance on this final exam question during these two consecutive years are compared.

In Spring 2015 students scores have the mean of 29.4% with the standard deviation of 43.5%, while in Spring 2016 the mean has more than doubled to 61.7% with the standard deviation of 42.0%. The difference in the results is statistically significant with t(59)=2.47, p=0.016. The result provide strong evidence that the integration of HandsOn-SEA and the proposed laboratory modules into the curriculum has a positive effective on student performance, in terms of improving the student understanding of the concepts related to force control and sensor-actuator non-collocation. Note that having unequal group sizes does not affect the result of a t-test.

Following observations are important while evaluating the results. Students are admitted to Sabanci University based on academic merit, with a nationwide centralized exam and performance of student population does not vary significantly between the classes of 2015 and 2016. Only a single student was repeating the course in Spring 2016. Furthermore, all students have been provided with the same sample exam for the last 3 years the course have been taught, where sensor-actuator non-collocation is explicitly listed as one of the major concepts about which a question is likely to be asked.

6.2 Promoting Algorithmic Thinking at K12 Level

In this section, we introduce an application which is created especially for the high school students showing that HandsOn-SEA is can not only be used for teaching subjects that are related to physics but also abstract subjects such as algorithmic thinking. We have selected sorting algorithms as the target applications as they constitute one of the most basic and essential group of algorithms.

6.2.1 Learning Description

Sorting algorithms provide a rich set of approaches that can be used to effectively demonstrate the fundamentals of algorithmic thinking. Along these lines, several sorting algorithms have been developed for use with force-feedback educational interfaces. The goal is to sort a given number of visually identical springs with respect to their stiffness levels. The force-feedback educational interfaces enables pairwise comparisons of any two springs by haptic rendering their stiffness. Once such a comparison is performed, the order of springs these springs can be switched as necessary. The use of an haptic interface not only enforces pairwise comparisons, but also provides an effective means of data hiding, as the stiffness levels of other springs becomes unavailable to the user during comparisons or sorting. An ideal training session takes place as follows: Students are first asked to familiarize themselves with the haptic interface and provided with a general set of instructions such that they have a common understanding of the main goals the task and means to achieve them. Then, students are asked to test themselves with a Free Run, during which they are free to select any two springs they want to compare and proceed with sorting as they wish. Free Runs are repeated several times with increasing number of springs to sort. With this step, it is aimed that the students gradually get a better appreciation for the importance of having a strategy to accomplish the sorting task in a systematic and efficient way. Next, students are asked to perform Guided Runs, during which an interactive user interface guides them through several sorting algorithms, including Bubble Sort and Insertion Sort. Before each such Guided Run, students are informed about the underlying idea of the algorithm by a set of instruction. During the Guided Runs, students are expected to closely observe the order comparisons that are performed, such that they learn how to make these comparison decisions by themselves. During Guided Runs, students are provided with visual feedback that highlights the important features of the underlying sorting algorithm, as well as several performance metrics related to the strategy. After completing the Guided Runs, students are asked to perform the algorithms by themselves in a Retention Run.

6.2.2 System Description

The application consists of a visual interface (GUI developed using Matlab) and a HandsOn-SEA. Any Haptic Paddle type interface can be adapted for use with the application. We have preferred to use HandsOn-SEA, as this interface features a very large force output capability providing a more perceivable interaction. The sorting applications input a certain number of identical looking springs with different spring ratios. The goal is to systematically sort the springs according to their stiffness. In the comparison phase, springs with lower and higher stiffness values are felt with predetermined spring rates. The GUI, implemented in Matlab, systematically guides the user to perform pairwise comparisons and swapping between relevant springs as necessitated by the algorithm. The use of haptic feedback for comparisons provides an effective means of data hiding, as the true stiffness of each spring becomes available only after physical interaction with that spring.

As we have done for the pHRI educational modules, we have used a TI F28069M type board as the micro-controller and programmed it using Simulink. The Simulink model is deployed to the micro-controller to set up a virtual environment in real-time. The virtual environment is rendered as a massless handle attached to two virtual springs from both the sides. This model receives the stiffness coefficients of the springs that are being compared online from the GUI, using serial communication bus. The model outputs the motor positions for use in visualization as depicted in the Figure 6.5

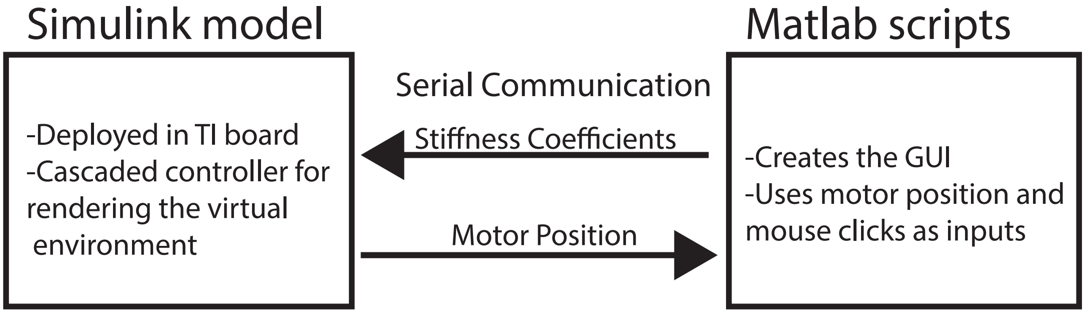


FIGURE 6.5: Application and GUI interface

6.2.3 Evaluation of Educational Efficacy

Educational effectiveness of Handson-Computing application have been evaluated through student surveys, student performance metrics.

Student Evaluations of HandsOn-Computing We have used HANDSON-SEA in a workshop to introduce HandsOn-Computing to 11 sophomore level students. Almost all of them have taken an introduction to computer science course but none of them were familiar with the sorting algorithms at the beginning of the workshop. Throughout the workshop students interacted with the device and aimed to fulfill the requirements of the application. Although it has taken more time for some students every student was successful in acquiring the presented knowledge in the guided learning phase and apply it in the testing phase. After the workshop, students filled in a questionnaire.

The statistical analysis of student responses revealed that the factor of major was not statistically significant at the 0.05 level for any of the survey questions; hence, all responses are aggregated for reporting. The Cronbach's α values have been calculated for the whole survey, and the α value is evaluated to be greater than 0.8, indicating high reliability of the survey.

The survey includes 5 questions: Q1 is assessing the properties provided by the haptic interaction, Q2 is for rating each part of the application separately, the usability, Q3 is for determination of target population, and Q4 aims to reveal the extent to which basic features of the application are useful, Q5 is for assessing essential aspects of HandsOn-SEA. For all of the questions, 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 6.2.

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

- Responses to Q1 demonstrate the students find the addition of haptic feedback benefits the application for all the proposed aspects listed in the question.
- From answers given to Q2, we can deduce that students find especially find the Guided Learning and Testing phases very useful.
- Responses to Q3 reveals that students regarded the application to be most useful for middle and high school students and there were also considerable support using the application in elementary school and university level.

Table 6.2: Survey Questions and Summary Statistics

Q1: How would you rate the importance of using the haptic interface/feedback for this application?	Frequency
Data hiding while demonstrating pairwise comparisons	87.5
Addition of another pathway to student perception	87.5
The novelty affecting/providing motivation	82.5
Enabling visually impaired students	87.5
For quantitatively tracking learning performance	85.0

Q2: Overall, how do you rate the usefulness of each mode of HandsOn-Computing?	Frequency
Exploration Phase	68.2
Guided Learning Phase - Bubble sort	84.1
Guided Learning Phase - Insertion sort	82.1
Testing Phase	81.8

Q3: How would you rate the usefulness of HandsOn-SEA for the following groups?	Mean	σ^2
Elementary school student(First five year)	3.54	1.36
Middle school(6th to 8th year)	4.18	0.75
High school student	4.18	1.25
University students	3.63	1.62

Q4: Please rate the following.	Mean	σ^2
Difficulty of sorting in Exploration Phase		
(i) with 4 elements	1.09	0.30
(ii) with 8 elements	3.72	1.36
Distinguishability of the stiffnesses of compared springs	4.72	0.38
Importance of using algorithms for higher element size	4.00	0.72
Usefulness of the Guided Learning Phase for the Testing Phase	4.27	0.56
Importance of adjustability of the element size	4.20	0.56
Overall usefulness haptic feedback	3.91	1.72

Q5: Please rate following aspects of HandsOn-Computing.	Mean	σ^2
Realism of the virtual environment	4.27	1.01
GUI, ease of use	4.18	0.75
Idea of teaching algorithmic thinking via HandsOn-Computing	4.55	0.69

- Answers to Q4 indicate that increasing element sizes are effective in instilling the requirement of using algorithms, the stiffness of the springs are distinguishable enough and the Guided Learning modes can effectively prepare the student for the Testing Phase.

- For Q5, the mean scores of individual features indicate that students *strongly* *appreciate* the idea of teaching algorithmic thinking via HandsOn-Computing. They also find the aspects related to performance of the device and the visualization successful.

Chapter 7

Generalizations and Extensions of HandsOn-SEA

HandsOn-SEA design can be utilized for building variety of applications that are essential to haptics and control engineering. Using two HandsOn-SEA devices students can be effortlessly build an admittance type pantograph or use one as master and the other one as slave to work on bilateral teleoperation. Students can also work on the well known, under-actuated ball and beam problem to practice their knowledge on control theory and sensor fusion.

In many cases with the educational devices, students spend a very long time getting familiar to the interface. Therefore modularity of an educational device is a very important property since the student can easily utilize the device for variety of different applications once familiar to the essential hardware features and software requirements. In the sections below, we introduce the desgn properties of our proposed extensions. On can view the devices while they are working by watching the related videos in our laboratory website[32].

Parameter	Description	Value	Unit
l_1	Length of the first link	113	mm
l_2	Length of the second link	115	mm
D	Distance between grounded joints	125	mm
α	Tilt angle between device bases	30	°

TABLE 7.1: Parameters of the 2-DoF version of HANDSON-SEA

7.1 Generalization of HandsOn-SEA to Multi Degrees of Freedom Devices

Single degree of freedom devices are very convenient for teaching fundamental concepts, such as the ones proposed in Section 6.

However, kinematic analysis and optimization of mechanisms are very important topics for a robotics student. Position and velocity level forward and inverse kinematics can be taught using multiple DoF devices. Moreover, wider range of virtual environment applications are possible for students to learn while using their creativity to build various virtual environment applications. Several two DoF implementation of haptic paddles are made in [33] and [34].

Our initial higher DoF model is a 5-bar linkage type pantograph mechanism. Converting two devices into a pantograph only requires several extra links to connect the end effectors.

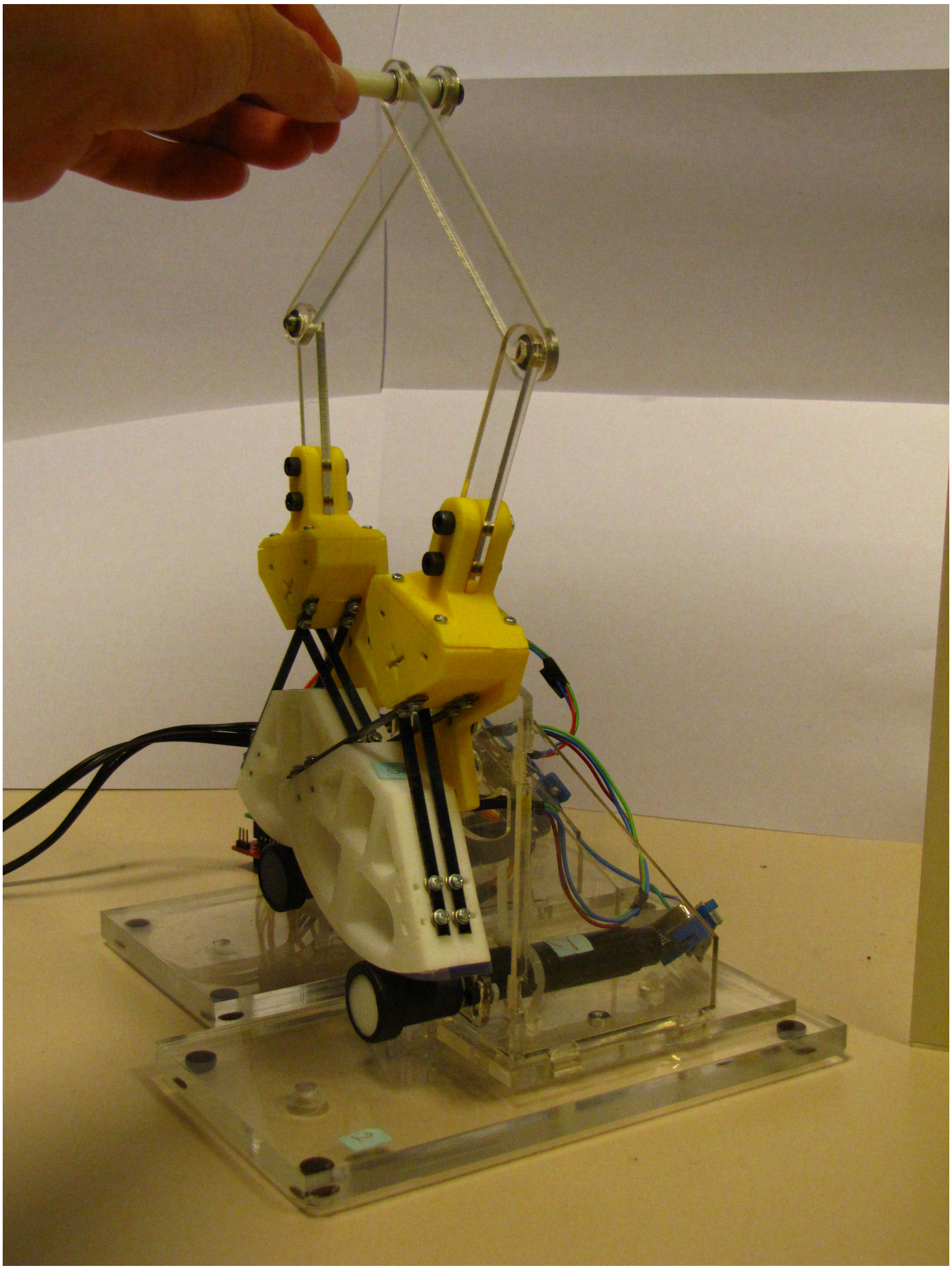


Figure 7.1: Pantograph mechanism created using 2 HandsOn-SEA

7.2 Ball and Beam

An implementation of a ball and beam mechanism is implemented using a Haptic Paddle by Rice University in the recent years [35]. In that project, the ball position information is harnessed via an IR sensor. The force sensing capability of HandsOn-SEA can be utilized for estimating the position of the ball. However, due to the noisy nature, of the hall effect sensor this task is not very easy. A non-model based controller was initially implemented but this controller resulted unstable behavior when the derivative of the hall effect sensor was utilized above a limit and resulted in a stable but undamped system otherwise. This version could be used for any balls that weighted between certain limits. A model based approach was made by designing a Kalman filter based observer for the position of the ball.

Unless the ball is very heavy, the maximum deflections made on the standard HandsOn-SEA is well below the limit. In order to increase the performance students can find creative ways. They can change the spring steels width after determining the stiffness of the cross-axis flexure element that would fit their needs the most. Another way to boost up the performance is to add extra magnets to the deflection measurement mechanism which will both result in reading a higher magnetic field strength for the given amount of deflection, and higher signal to noise ratio.

The detailed model of this mechanism can be found in Appendix C.

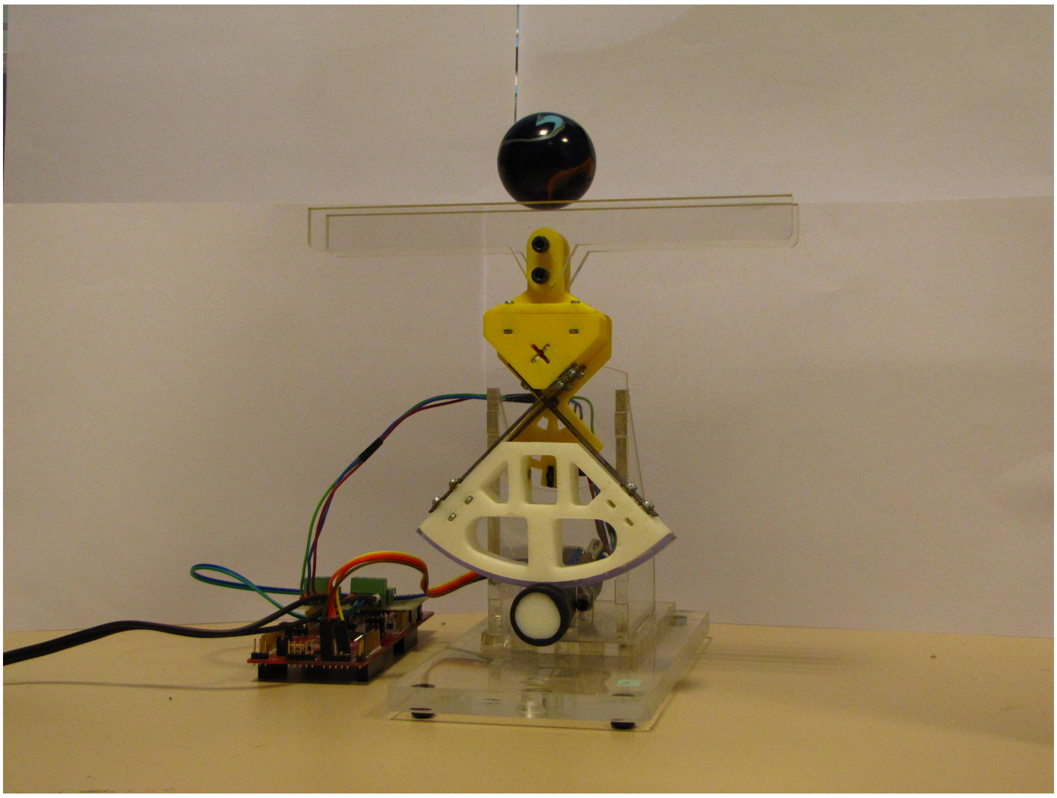


FIGURE 7.2: Ball and beam mechanism

Parameter	Description	Value	Unit
θ_m	Motor angle	Variable	rad
θ_b	Beam angle	Variable	rad
x_b	Position of the ball	Variable	mm
v_b	Velocity of the ball	Variable	mm/s
I_b	Inertia of the beam	118.0	$kgmm^2$
I_{bl}	Inertia of the ball	14.5	$kgmm^2$
m_{bl}	Mass of the ball	88	g
r_{ball}	Radius of the ball	20.3	mm
r_{bl}	Effective rolling radius of the ball	18.7	mm
k	Rotational stiffness of the elastic element	3.96	Nm/rad
L	Length of the beam	200	mm
l_1	Length from the pivot to COM of the beam	45	mm
l_2	Closest distance from the pivot to top of the beam	80	mm

TABLE 7.2: Parameters of the ball and beam mechanism

Chapter 8

Conclusions

A single degree-of-freedom force-controlled educational robot with series elastic actuation has been proposed. Several prototypes of the robot have been built based on a various cross-flexure pivots and controlled in real-time using low-cost microcontrollers and PWM motor drivers. The force control performance of the device has been experimentally characterized.

Guidelines for educational use, as well as detailed laboratory modules have been provided for the integration of the device into pHRI related engineering courses. HandsOn-SEA has been evaluated in a senior level Introduction to Robotics course and shown to be effective in teaching the fundamental concepts in force control. Complementing the existing impedance-type designs educational robot designs, the statistically significant increase in student performance indicates that HandsOn-SEA is especially effective in demonstrating the inherent limitations of explicit force control, due to the detrimental effects of sensor actuator non-collocation.

The design and controllers of HandsOn-SEA have been developed to promote do-it-yourself philosophy. The surplus DC motor used in our prototypes can be replaced with a stock motor and encoder to ensure use of standard and widely-available components. All design files and software required to operate HandsOn-SEA are shared at `http://hmi.sabanciuniv.edu/?page_id=992` under GNU General Public License and the designs are continually updated for wider availability, lower cost, and better robustness. The bill of materials and the build guide are also shared at Appendix A and B respectively.

The design of HandsOn-SEA is primarily aimed as a low cost educational device; however, the cross-flexure pivot integrated sector pulley design can be generalized to and implemented in any force-feedback device with a power transmission that relies on a (sector) pulley. In particular, these devices can be transformed into force feedback robotic interfaces with SEA by replacing their (sector) pulleys with the proposed compliant versions.

There are three main modular extensions to HandsOn-SEA design that we are currently aiming at utilizing for engineering education in the near future. The first one is to analyze and optimize the workspace of 2DoF version. The ball and beam version is an under-actuated and inherently unstable model offering students an interesting system to exercise their control theory knowledge on. Lastly HandsOn-SEA can be utilized to teach students bilateral teleoperation simply by plugging in an additional HandsOn-SEA device to the same micro-controller and incorporating the required control architecture.

Future works include multi-criteria design optimization [36] of the cross-flexure pivot to achieve an ideal compromise among the system bandwidth and force control fidelity and out-of-plane deflections, as in [11].

Appendix A

Bill of Materials

We offer HandsOn-SEA as a low cost, easy to build and open source device whose manufacturing files and bill of materials are available in our laboratory website. In this section the bill of materials is also offered to the readers.

Part	Amount	Description
Plexiglass base (Base) - Thickness: 5 mm	1	All the stl and dxf files for laser cutting and 3D printing can be found in the manufacturing files folder
Plexiglass base (Side) - Thickness: 5 mm	2	
Plexiglass base (Face) - Thickness: 3 mm	1	
(Alternative) 3D printed base	1	
Plexiglass motor holder - Thickness: 2-3 mm	1	
3d printed pulley	1	
3d printed handle base	1	
3d printed handle top	1	
3d printed pinion	1	
(Optional) Plexiglass Lower Plate	1	
Heat shrink tube for pinion	-	Wrapped around the pinion for increasing friction. This must be wider than the pinion which is 18 mm in diameter
Bearing (Inner D: 4 mm, Outer D: 10 mm)	1	Outer diameter: inner diameter: To be attached to the face of the base
Nuts (2 mm)	17	The amount can be reduced using less screws per steel sheets. For increased rigidity purposes the spring steels were fastened using 8 screws (4 top 4 bottom).
Screws (D:2 mm, L: 10 mm)	8	
Screws (D:2 mm, L: 15 mm)	8	
Washers (2 mm)	16	
Screws (D:2 mm, L: 5-6 mm)	2	For connecting the motor to the motor holder
Nuts (3 mm)	1	On the tip of the shoulder screw and mounted in the handle part
Washers (3mm)	1	This goes in between the handle and the face part of the base for reducing friction.
Screws (D:4 mm, L: 10-20 mm)	2	To connect motor holder to the base
Nuts and washers (4mm)	1	
Lasercut spring steel sheets	4	Dimensions can be found from the dxf file
TI Launchpad F28069M	1	This board has good compatibility with Simulink and has a built in quadrature encoder reader
TI DRV8801 driver	1	This can be mounted on the PCB whos files are provided

Part	Amount	Description
Resistors for voltage divider	2	Two resistors can be used to create a voltage driver circuit, used to drop the voltage from 0-5V to 0-3.3 V range. 1.5 and 2.7 kOhm were used but can vary. Make sure the resistance values are high enough though.
PCB	1	Eagle Files can be found in the folder. We used an available one layer PCB it can be made better using a two layer one.
Motor currently used: Maxon re16 with 1:84 gear and 16 cpt encoder"	1	This type was available in our lab but other types of motor can be used as well. 1:29 gear can work better
(Alternative) Motor:	1	Medium power 26mm pololu motor with encoder and 1:47 gear reduction
24 V, I 3A Power Source	1	
3 pin Pitch: 0.15" PCB connector (header and plug)	1	This is for connecting the cables of hall effect sensor to PCB
4 pin Pitch: 0.15" PCB connector (header and plug)	1	This is for connecting the power supply and motor input cables (2 for each) to the PCB
Cables for connecting power source to the driver, encoder and hall effect sensor to TI microcontroller	9	We have used jumpers for 4 encoder and 2 motor input cables. Normal cables were used between the power source and the driver. 3 normal cables were also soldered to the hall effect sensor
Heat shrink tube for soldered wire connections	-	Size depends on the wire width.
4*4*4(mm) Neodium magnet cubes	2	
Single and double row 1" female pin headers	-	3 single row for sensor. At least 4 single row and 5 single and 5 double row on the PCB
Plain PVC table cover. Thickness: 3mm	1	For the width, 15 mm worked fine for us in general but better to cut after manufacturing other parts. This material is used to increase friction, neoprene rubber is a good alternative.

Appendix B

Build Guide

B.1 Assembling the base

- Components
  - Plexiglass base (Base)
  - Plexiglass base (Side)
  - Plexiglass base (Face)
  - Bearing
  - Plexiglass base (Lower plate)(Optional)
  - Super glue
  - Cloroform (Optional)
- Procedure
  1. Glue one of the sides parts and face part together.
  2. Glue the other face part to the assembly.
  3. Glue the assembly into the plexiglas base.
  4. Glue the bearing into the face.
  5. Use glue or cloroform to fix the base assemly on the lower plate (Optional)

B.2 Assembling the Handle, Pulley and spring steels

- Components
  - 3D printed pulley
  - 3D printed handle
  - 4x spring steels
  - Hall effect sensor
  - 3 pin single row pin header
  - 8x screws(D:2 mm, L: 15mm)
  - 8x screws(D:2 mm, L: 10mm)
  - 16x 2mm nuts and washers
  - Screw driver
  - Tooth pick
  - Positioning base
- Procedure
  1. First take out the metal pieces and then glue the 3 pin female header on the handle.
  2. Mount the hall effect sensor into the handle.
  3. Solder the legs of the hall effect sensor with cables, use heat shrink tubes and hot glue gun to protect the legs.
  4. Mount the cube magnets into the pulley with each magnet facing the same pole towards each other
  5. Screw in the metal strips on the handle part. Using a toothpick and positioning base is very handy for alligning the screws with nuts.
  6. Screw in the metal strips on the pulley part.

Note: This is the only time consuming part of the assembly.

B.3 Mounting the motor and top

- Components
  - Motor
  - Pinion
  - Motor holder
  - Shoulder screw
  - 3 mm thick PVC table cover
  - 3mm washer
  - 2x D:2 L:5 mm screws
  - Heat shrink tube (wider than pinion)
  - Hot air gun
- Procedure
  1. Cut a piece of PVC table protector and paste it along the circumference of the pulley part as it is shown in the figure. The width of the PVC strip that we use is 15mm but this can vary. The thickness can also vary.
  2. Use the shoulder screw and a washer to screw the handle part to the face through the bearing.
  3. Screw the motor holder on the motor.
  4. Using a hot air gun wind a heat shrink tube around the pinion to avoid slip. Pinion's tip has a greater radius for restraining the pulley from tilting forwards during operation.
  5. Place the pinion on the shaft of the motor. If this assembly is not tight enough the pinion can fall during the operation.
  6. Screw the motor holder on the base. The motor holder should be in front of the face.
  7. The height adjustment of the motor should calibrated. Pinion should exert just enough force on pulley to provide desired friction.

B.4 Creating the PCB

- Components
  - Pressed/Printed Circuit Board
  - 2x Resistors
  - DRV 8801 Driver
  - Benchtop drill press
  - 3 pin PCB connector
  - 4 pin PCB connector
  - Single and double row 1” female pin headers
- Procedure
  1. Using the Eagle files press the raw circuit board
  2. Drill through the required holes
  3. First solder the legs (male pin headers) of DRV8801 on the PCB, then solder the DRV8801.
  4. Selection of resistors for the voltage to drop the voltage from 0-5V to 0-3.3 V range. 1.5 and 2.7(green one) kOhm were used but can vary. Make sure the resistance values are high enough though.
  5. Place in and solder the other required components.

B.5 Electronic Assembly

- Components
  - PCB
  - TI F28069M Microcontroller
  - HandsOn SEA mechanical assembly
  - Jumper wires
  - 24 V power supply
  - Screw driver
- Procedure
  1. Place the PCB on the microcontroller
  2. Connect the hall effect sensor to 3 pin PCB connector
  3. Plug in 6 male ends of female to male jumper wires on the motor's connector. Using different type of motor would of course change this step.
  4. Connect the power supply wires and the motor energy supply wires to 4 pin PCB connector.
  5. Plug in both PCB connectors and place the PCB on the microcontroller
  6. Plug in the quadrature encoder wires (GND, 5V, A, B) to their corresponding positions on the microcontroller

Appendix C

Modeling of Ball and Beam Mechanism

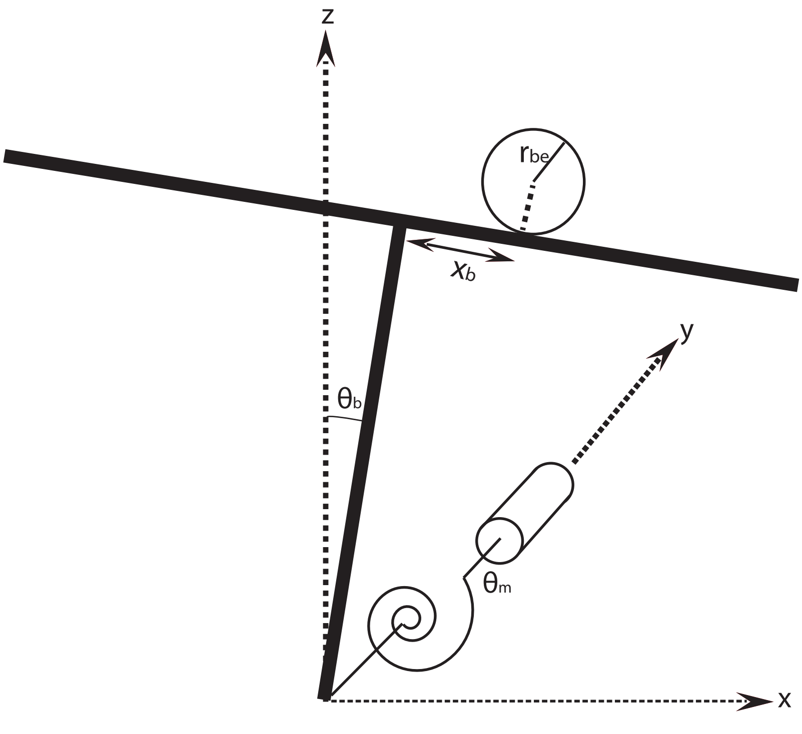


Figure C.1: Schematic view of the ball and beam mechanism

$$M = \begin{bmatrix} I_m & 0 & 0 \\ 0 & I_b + I_{bl} + m_b l_1^2 + m_{bl}((l_2 + r)^2 + x^2) & I_{bl}/r + m_{bl}(l_2 + r) \\ 0 & I_{bl}/r + m_{bl}(l_2 + r) & m_{bl} + I_{bl}/r^2 \end{bmatrix}$$

$$h = \begin{bmatrix} 0 \\ 2m_{bl} x \dot{\theta}_b \dot{x} \\ -m_{bl} x \dot{\theta_b}^2 \end{bmatrix}$$

$$\phi = \begin{bmatrix} k(\theta_m - \theta_b) \\ -k(\theta_m - \theta_b) - g(l_1 m_b sin(\theta_b) + m_{bl}(xcos(\theta_b) + (l_2 + r)sin(\theta_b))) \\ gm_{bl} sin(\theta_b) \end{bmatrix}$$

The dynamics can be expressed as:

$$M(q)\ddot{q} + h(q, \dot{q}) + \phi(q) = T \text{ where } q = \begin{bmatrix} \theta_m \\ \theta_b \\ x \end{bmatrix} \text{ and } T = \begin{bmatrix} T \\ 0 \\ 0 \end{bmatrix}$$

The ball position can be estimated considering the quasi-static case, using the motor position and spring deflection(θ_{def}) parameters.

$$M_{measured} = M_{beam} + M_{ball}$$

$$where$$

$$M_{measured} = k(\theta_{def} = k(\theta_m - \theta_b)$$

$$M_{beam} = g(l_1 m_b sin(\theta_b))$$

$$M_{ball} = gm_{bl}(xcos(\theta_b) + (l_2 + r)sin(\theta_b))$$

$$resulting\ in$$

$$k(\theta_m - \theta_b) = g(l_1 m_b sin(\theta_b) + m_{bl}(xcos(\theta_b) + (l_2 + r)sin(\theta_b)))$$

$$from\ which\ x\ can\ be\ extracted.$$

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