Teaching With Hapkit

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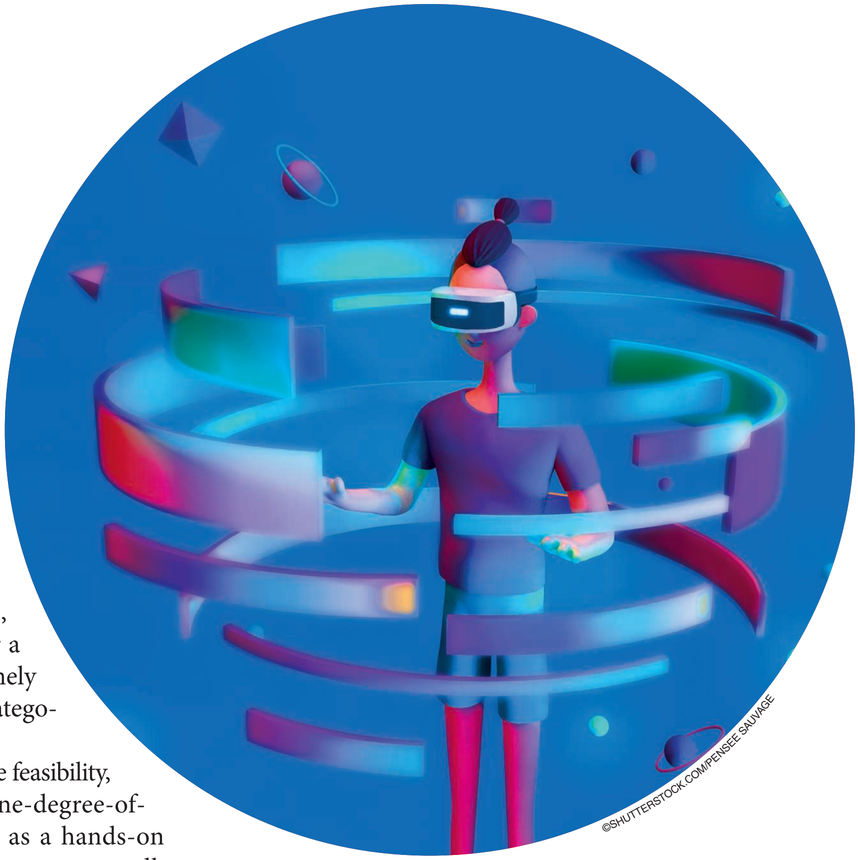
Enabling Online Haptics Courses With Hands-On Laboratories



Online learning is an important aspect of higher education today. One-third of college students take at least one course online, and almost 70% of chief academic leaders say that online learning is critical to their long-term strategy [1]. Despite the success and growth of online education, the number of courses that currently offer a hands-on laboratory component is extremely limited, resulting in the lack of an entire category of engineering courses.

The goal of this article is to understand the feasibility, benefits, and challenges of including a one-degree-of-freedom (1-DoF), low-cost haptic device as a hands-on laboratory component of two online courses—a small, instructor-guided course and a large, self-paced massive open online course (MOOC). The field of haptics refers to interactions that involve the sense of touch, and, as in many engineering topics, it requires labs to enable full understanding. We present here a low-cost, open source, easy-to-assemble haptic device called *Hapkit* (Figure 1) along with our curriculum design, aimed to fill the void in hands-on laboratories in the space of online engineering courses.

The results and feedback about the hands-on laboratories were positive, motivating further development in this area. In particular, the strong preference indicated toward physical hardware, rather than a computer simulation, illustrates the potential for online courses with hardware components. This approach to teaching and learning is considered especially important in light of recent situations requiring social distancing.

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Background

Laboratories for Remote Learning

Laboratory experiences are an integral part of engineering education [2], with several studies showing the benefits—including improved retention rates and an improved ability to solve open-ended problems—of incorporating hands-on, applied courses early and often [3]. To enhance the learning of remote or online students, three main methods for conducting labs have been explored: fully virtual setups, shared physical hardware controlled remotely, and individual physical hardware at each student's learning site.

Virtual laboratories where the infrastructure and experiments are entirely simulated [4], [5] can be relatively inexpensive and have been developed for several different engineering topics [6], [7]. Although promising for teaching a certain level of conceptual understanding, it appears difficult to effectively teach design skills and the ability to tackle

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open-ended situations using virtual labs, at least in their current form [4].

Researchers have also investigated the use of a single set of hardware that students can operate remotely over the web. For example, Gillet et al. described using a number of electromechanical systems, including an inverted pendulum and a model helicopter, to allow students to remotely adjust controller parameters and view the system responses [8]. This setup provided students with practical experience in control engineering without requiring them to be in the same location or have their own hardware.

There have been a few examples of equipment that aimed to enable each student to have individual hardware at his or her remote location. For example, two take-home lab kits, consisting of a mass-spring-damper system and an analog filter system, were developed and distributed to students to take home and use similarly to regular assignments [9]. However, this pilot project was not designed with the intent for the devices to be distributed on a larger scale. Similarly, the Andruino-A1 is a low-cost, modular, and extendable mobile robot that students can construct and program themselves. It was designed for use in both classroom and online courses but, to date, has been used only in a traditional classroom [10].

Educational Haptic Devices

Most commercial haptic devices are too expensive and complex for a classroom setting. In addition, they are usually proprietary, making it difficult for users to modify or extend the hardware to enhance learning. In 2002, researchers at Stanford University designed a simple 1-DoF device, called the *Haptic Paddle*, for use in a dynamic systems course [11] [Figure 2(a)]. Students used the device to interact with virtual environments and learn how to model, analyze, and control dynamic systems. Due to the success of integrating a lower-cost haptic device with a standard engineering course, several other universities adopted the idea, modifying the Haptic Paddle to better fit their teaching objectives [12].

There are several features common to all Haptic Paddles to date. First, they are 1-DoF devices, keeping the cost relatively low compared to typical 3-DoF commercial devices. Additionally, they are impedance-type force-feedback devices driven by an electromagnetic actuator. Finally, the user typically interacts with them through a joystick-like handle. Several versions of the Haptic Paddle are shown in Figure 2. The design of each reflects the differences in learning objectives as well as intended audience.

Hapkit Device

Hapkit, shown in Figure 1, is a 1-DoF, kinesthetic haptic device. The name, *Hapkit*, is derived from "haptic kit," because students start with a kit that has the components needed to assemble the device themselves. To ensure that students could assemble, program, and interact with this device in an online learning environment without an instructor physically present, we implemented a number of important design changes and features compared to the original Haptic Paddle. We highlight the features for two iterations of the design—Hapkit 1.0 and Hapkit 2.0—which were created for use in a guided, online pilot course and a self-paced MOOC, respectively. A list of parts and prices can be found at http://hapkit.stanford.edu, and the approximate total cost of parts and tools for Hapkit 1.0 and 2.0 was US$100 and US$50, respectively.

Mechanical Design: Hapkit 1.0

Three main factors drove the device design: cost, learning environment, and users. First, because students would ultimately purchase the kit themselves, it was important that the device be as inexpensive as possible. Second, unlike standard in-person learning environments, there would not be an instructor physically present, so the design needed to be self-explanatory and easy to assemble using only household tools. Third, the design had to be accessible to users from a wide range of backgrounds, including those without any prior building experience.

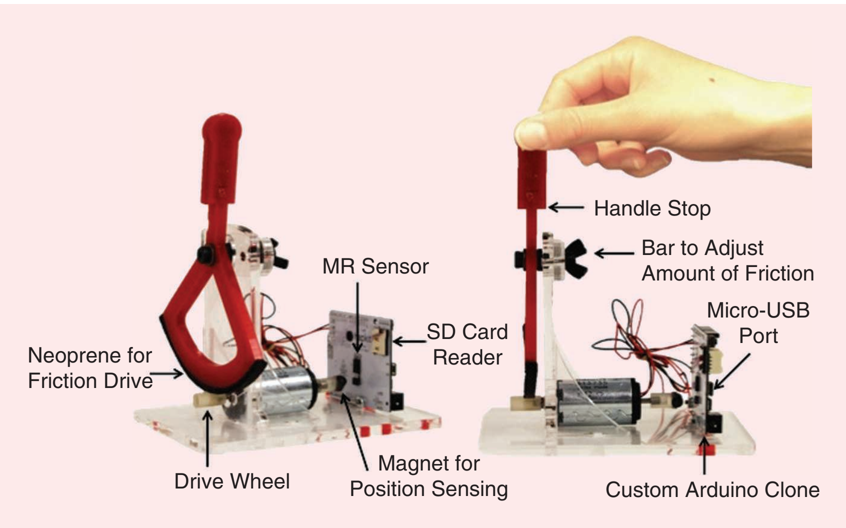

Figure 1. A fully assembled, 1-DoF, low-cost, open source haptic device, Hapkit, used in hands-on laboratories in an online course. Design features that ensure students could assemble, program, and interact with this device in an online learning environment are highlighted. MR: magnetoresistive; SD: Secure Digital.

Step-by-Step Assembly

Unlike previous Haptic Paddles, Hapkit was intended for students to build completely on their own using a kit, shown in Figure 3(a), which includes all of the components and tools necessary for assembly. The main body of Hapkit is made of laser-cut acrylic pieces. To ease assembly, a number is etched onto each of these pieces [Figure 3(b)] as well as a series of tabs and corresponding holes on parts meant to connect. Glue, three hex keys, and a small flathead screwdriver are the only tools required. A list of parts, tools, and cost are provided in the Hapkit 1.0 section of the project website, http://hapkit.stanford.edu.

Friction Drive

The original Haptic Paddle, along with several successors at various universities, used a capstan drive mechanism [11], [15]. This design requires winding a thin cable around a capstan (which is attached to the motor) several times and then properly tensioning the cable enough to transmit forces from the motor to the sector pulley. Recently, a few universities, including Vanderbilt and Rice University, have switched to using a friction drive mechanism [13], [14]. In these versions, the forces from the motor drive wheel are directly transmitted to the sector pulley, since they are in direct contact.

There is a tradeoff between the complexity and performance of these two drive mechanisms. Despite the ability of capstan drive devices to render high virtual stiffnesses, the process of winding and tensioning the cable can be difficult and tedious, especially for novice users, and it is often easiest to do with a partner. Alternatively, a friction drive, while adding a considerable amount of inherent damping to the system, is far less complicated to assemble. After initially attaching a piece of neoprene rubber to the bottom edge of the sector pulley, the amount of friction can be easily adjusted by raising or lowering the bar shown in Figure 1. If the device becomes unstable,

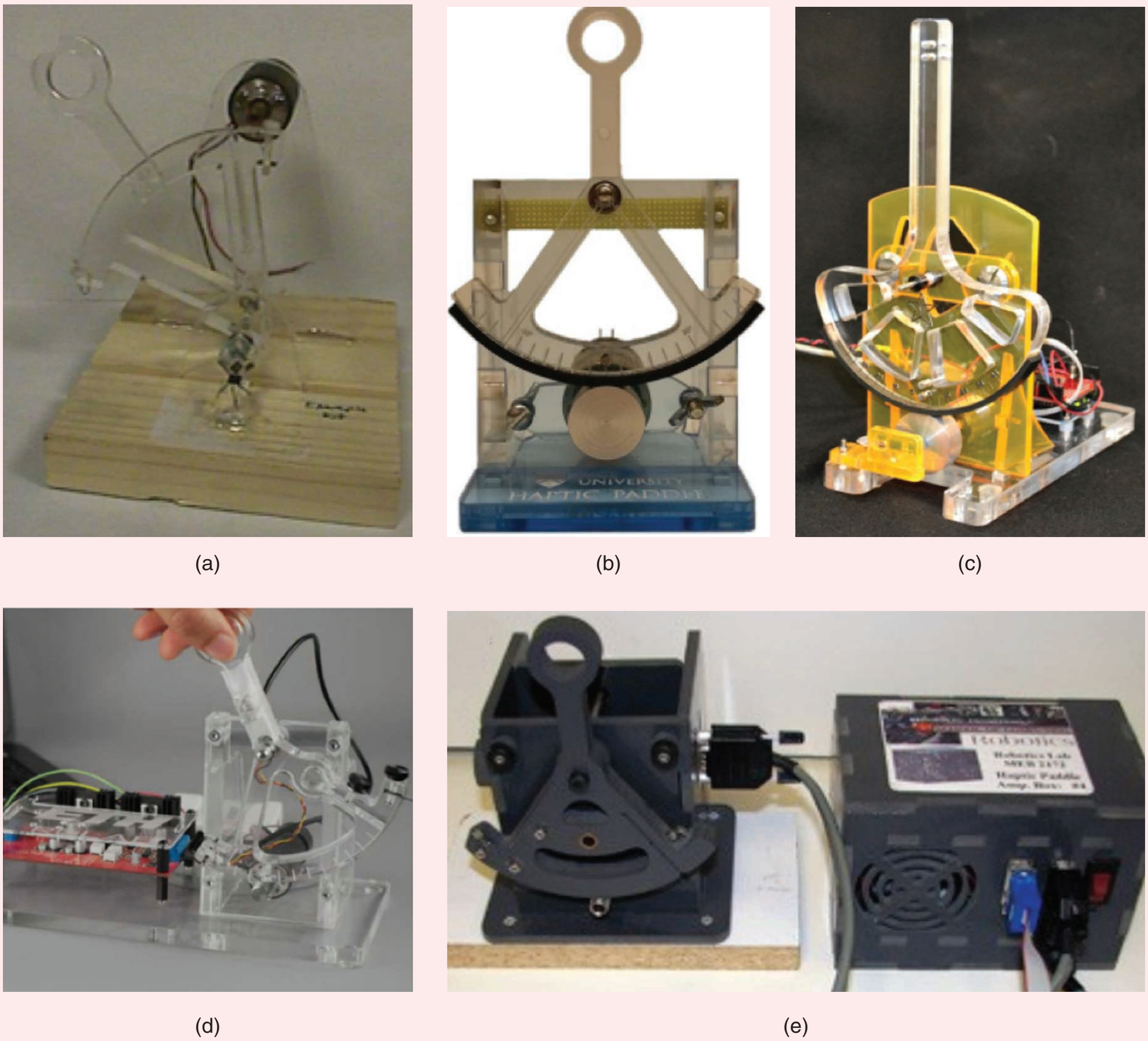

Figure 2. (a) The original Haptic Paddle from Stanford University [11]. (b) and (c) Friction drive Haptic Paddles from (b) Rice University [13] and (c) Vanderbilt University [14]. (d) and (e) Capstan drive Haptic Paddles from (d) ETH Zurich [15] and (e) the University of Utah.

students simply rotate the sector pulley until it is back in contact with the drive wheel.

An additional design feature that helps students easily reset the device if it goes unstable is the handle stop, shown in Figure 3(c). If the motor forces the sector pulley hard enough in one direction so that it loses contact with the drive wheel, the handle stop hits the top of Hapkit, preventing the sector pulley from continuously spinning. This feature prevents Hapkit from self-damage of the handle, since it cannot collide with the spinning drive wheel, as well as from wearing of the neoprene, which does not contact the spinning drive wheel.

Drive Wheel Size

Another important design choice was the size of the drive wheel. Because the radius of the drive wheel, radius of the sector pulley, and length of the handle determine the force felt by the user, as shown in (2), it was important to have a smaller drive wheel to increase the force felt. A smaller drive wheel also results in higher-resolution sensing, since there are more rotations of the magnet (used for sensing) per distance traveled of the sector pulley and, therefore, more position sensor readings per distance moved by the handle.

Mechanical Design Updates: Hapkit 2.0

Hapkit 1.0 was designed for a guided online pilot course, where each student would receive all parts necessary for building his or her own device. Laser cutting the sector pulley, base, and mounting pieces was therefore the most efficient method, since we had to fabricate more than 100 kits.

However, once the online course shifted to a self-paced version, where students had to acquire all Hapkit components themselves, we needed to redesign Hapkit to make it more accessible for individual students. The main change from Hapkit 1.0 to 2.0 was to make the components easy to 3D print, rather than laser cut, since 3D printers are far more ubiquitous, often found in libraries and post offices. We also wanted to be sure that the components could be successfully printed using low-cost printers, such as a Makerbot, which are more widely available and affordable.

Electrical Design Features

Custom Printed Circuit Board

One of the most significant modifications from previous Haptic Paddles was the development of a custom printed circuit board (PCB). Our PCB, called the *Hapkit Board*, is an Arduino clone that uses the same Atmega 328 microprocessor as an Arduino Uno [16]. It is compatible with regular Arduino shields and can be programmed using the Arduino programming environment, making it versatile and giving students the opportunity to use the board after the class ends for other projects. However, rather than using an off-the-shelf board, it was significantly more cost effective to develop our own board that included all of the necessary electronics for Hapkit, including motor-driving circuits, a position sensor, and a Secure Digital (SD) card

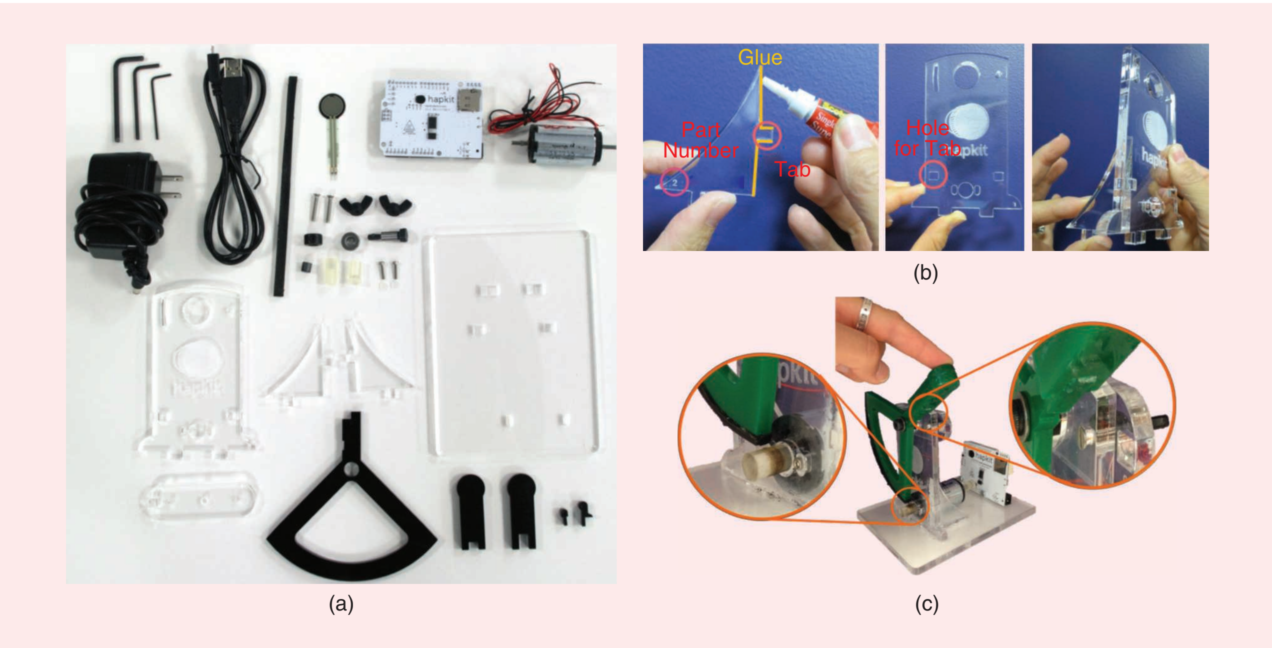

Figure 3. (a) The Hapkit components, including laser-cut acrylic pieces, 3D-printed parts, custom PCB, motor, various nuts and screws, power supply, micro-USB cable, and tools needed for assembly. (b) The simple assembly process features laser-etched numbers on each acrylic piece along with a series of tabs and slots to enable easy connection of corresponding pieces. (c) The handle stop is designed to prevent the sector pulley from continuous rotation that would otherwise cause the handle to collide with the spinning motor and break.

reader. The Hapkit Board is available for purchase from Seeed Studio (https://www.seeedstudio.com/) for US$35 (compared to more than US$50 for an Arduino Uno and motor-driving shield alone). Another benefit of the custom board is that it includes mounting holes for the magnetoresistive (MR) sensor. These holes allow the sensor to be mounted flat against the board to prevent the leads from breaking while also aligning the sensor head with the magnet on the motor shaft.

MR Sensor

As previously mentioned, an MR sensor, the KMA 210 from NXP Semiconductors, was used as the position sensor. It has an angle resolution of 0.04° and a linear output corresponding to a range of 0–180°. In bulk, the MR sensor costs less than US$3.50, making it significantly cheaper than using an encoder, which is the most common position sensor used on other Haptic Paddles.

Software and Control

The software to control Hapkit is programmed using the Arduino programming environment and uploaded to the Hapkit board where it then runs closed-loop. Once the underlying kinematics and motor torque-to-force relationship have been programmed, various 1-DoF virtual environments can be rendered.

The basic control of Hapkit depends on computing an output force based on the position of the handle. The control loop begins by reading in the value of the MR sensor, which represents the angle of the motor pulley, θ_{pulley}, and mapping this to an angle of the sector pulley, θ_{sector}, based on an initial calibration. This calibration can easily be done using the lines that are laser etched onto the sector pulley every 10° [Figure 4(a)]. Approximating the movement of the handle as linear, the position of the handle, x_{handle}, can be calculated using relationships between the kinematic variables shown in Figure 4(a) and given by

$$x_{\text{handle}} = \frac{r_{\text{handle}} r_{\text{pulley}}}{r_{\text{sector}}} \theta_{\text{pulley}}. \tag{1}$$

Once the position of the handle is known, the desired output force at the handle can be calculated depending on the virtual environment or control law being rendered. The last step is to compute the motor torque, T_m, needed to output the desired force at the handle, F_{handle}, using

$$F_{\text{handle}} = \frac{r_{\text{sector}}}{r_{\text{handle}} r_{\text{pulley}}} T_m. \tag{2}$$

Rendering Virtual Environments

A number of different 1-DoF virtual environments have been implemented using Hapkit, which is typically capable of outputting up to 4 N of force. A virtual wall is a simple example, where the force output at the handle is given by

$$F_{\text{handle}} = -k(x_{\text{handle}} - x_{\text{wall}}), \tag{3}$$

if on one side of the virtual wall, and zero otherwise [Figure 4(b)]. The maximum renderable stiffness is approximately 200 N/m. In addition to rendering forces dependent on the position of the handle, it is possible to render velocity-dependent forces, such as damping, by estimating the velocity using the position measurements, loop time, and a low-pass filter. Using the resulting velocity along with the position measurements, a wide range of virtual environments can be rendered, including, for example, textures, mass-spring-damper systems, teleoperation schemes (if there are two Hapkits available), bumps and valleys, and springs.

The Design of an Online Haptics Class

Learning Objectives

For both the guided and self-paced courses, students learn how to build, program, and control haptic devices, that allow users to feel the components in a virtual or remote environment. In the process, students gain an appreciation for the capabilities and limitations of human touch; develop an intuitive connection between the equations that describe physical interactions and how they feel; and gain practical

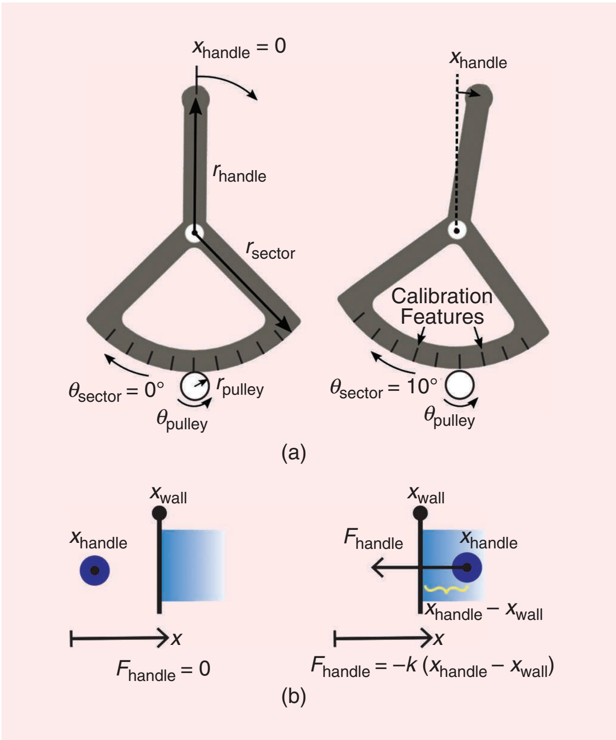

Figure 4. (a) The kinematic variables used to describe Hapkit, where x_{handle} is the handle position; r_{handle}, r_{sector}, and r_{pulley} are the handle, sector, and pulley radii, respectively; and θ_{sector} and θ_{pulley} are the sector and pulley angle, respectively. The calibration features are marked on the sector pulley every 10° to help map the MR sensor readings to the angle of the sector. (b) A graphical representation of the algorithm for rendering a virtual wall. If the handle position (x_{handle}) is greater than the position of the virtual wall (x_{wall}), then a force proportional to the difference between these values is rendered to the user (F_{handle}); otherwise, no force is rendered.

interdisciplinary engineering skills related to robotics, mechanical engineering, electrical engineering, bioengineering, and computer science. This course focuses on the design and implementation of haptic technology while addressing other topics, as needed, to motivate the course content and place it in context. By the end of this course, we expected students to be able to

- assemble, program, and simulate haptic virtual environments with their own haptic device
- identify the primary mechanisms of human haptic sensing
- understand methods for sensing the position of and actuating haptic interfaces
- identify salient features of a haptic device design
- list a variety of different types of haptic interfaces
- implement virtual environments to render various dynamics (e.g., stiffness or damping)
- describe the applications of haptic devices
- develop a new haptic device or application.

By successfully meeting these objectives, students are prepared for more advanced development and study, not only in the field of haptics but also in other fields, such as robotics and mechatronics. The required background for this course is high school physics (noncalculus) and precalculus. Beginning programming experience is helpful. Haptic device design, robotics, and mechatronics experience were not required—this was designed as a gateway course for these topics.

Table 1. The modules of the online haptics course.

Module Numbers and Topics
1) Introduction to haptic technology and human haptics
• Introduction to haptics
• Human haptics
• Applications of haptic technology
2) Hapkit mechanical design and assembly
• Design of kinesthetic/force-feedback haptic devices
• Example kinesthetic haptic devices
• Kinematics
• Force/torque relationships
3) Hapkit mechatronics
• Introduction to the Hapkit Board
• Position sensors for haptic devices
• Actuators of haptic devices
• Force-sensitive resistors (optional)
• Hapkit Board analog inputs/outputs
• Arduino programming language (optional)
4) Programming virtual environments
• Haptic rendering
• Rendering haptic effects
5) Mechanical characterization and simulation
• Recording and modeling mechanical interactions
• Validating a simulation

Course Content

This course had two types of offerings. The first was a real-time (instructor-paced) course where modules were posted weekly and students had to complete the viewings, online quizzes, and laboratory assignments on a weekly basis. The second (and ongoing) course was self-paced, so students completed the videos, quizzes, and lab assignments on their own schedules. Grading was automated in both cases. The demographics of students in the two courses were different, as reported in the "Results" section.

Both courses are divided into five modules, and we recommended that students complete one module per week. In each module (shown in Table 1), participants view online lectures, take online quizzes (interspersed with the lectures), and complete a laboratory assignment. Each module is expected to take about 10 h of student time, although this could vary widely depending on the student's background and experience. The pass/fail grade is based on quiz responses (50% of the grade) and submitted laboratory data (50% of the grade).

To receive a Statement of Accomplishment for this course (i.e., a passing grade), students must receive a score of at least 50%. This means that students likely must do at least some parts of the laboratory component to "complete" the course. (The first lab does not use Hapkit, so it is possible to pass without building one. This was meant to make the course more accessible to people without the necessary resources to make a Hapkit.) The current instantiation of the MOOC version of the online course can be accessed free of charge at http://hapticsonline.class.stanford.edu.

Hands-On Laboratories

To fully participate in lab assignments, participants need to acquire/build the components of a Hapkit and assemble and program the device. Laboratory assignments using Hapkit give participants hands-on experience in assembling mechanical systems, making circuits, programming Arduino-based microcontrollers, and testing their haptic creations (Figure 5). All students in the guided course were mailed Hapkit parts, whereas, in the self-paced MOOC, only some of the students purchased the components for and assembled a Hapkit. We estimate that number to be approximately 325, based on the number of students who received a perfect score on the second lab module, as explained in the "Results" section. The five laboratories were designed to be performed by the student without instructor supervision, using readily available household materials and the provided Hapkit parts list.

The first laboratory assignment addressed human haptics, and students were asked to perform a simple experiment, known as the *two-point discrimination test* [17], at home. This test seeks to determine, for a specific location on the body, the distance between two contact points at the threshold of when they are perceived as a single contact point versus two separate ones. We chose this assignment because it shows the process of developing a haptic experiment with human users and the results are meaningful for the design of haptic interfaces. Students entered the results of their test online, and we released the class average and standard deviation for tactile acuity at the tip of the index finger, the volar surface (inside) of the forearm, and the lower back.

In the second laboratory assignment, students constructed Hapkit using a detailed document with assembly instructions and a video that demonstrated and explained each step. For the guided course, students submitted pictures of their assembled Hapkits from the front, side, and back (Figure 6). We collected these images and visually inspected them to verify that the assembly was complete and correct.

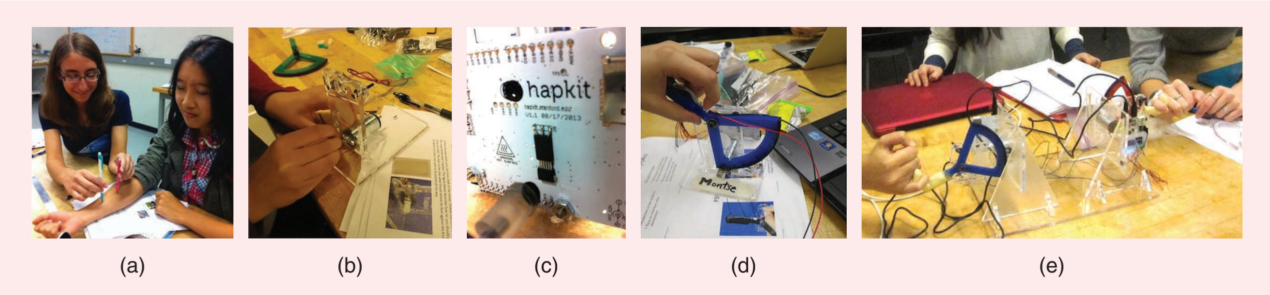

Figure 5. Images of laboratories corresponding to each module of the online class: (a) human haptics, (b) Hapkit assembly, (c) mechatronics, (d) haptic rendering, and (e) complex virtual environments. The images are from an in-person class at Stanford University, held in parallel with the guided online class.

Figure 6. The students in the guided course built and submitted front-view images of their Hapkits during Lab 2.

For the MOOC, students submitted several measurements of the sizes of the components of their Hapkits. Taking such measurements required the students to acquire some of the physical components of Hapkit, although this was not proof of successful assembly. Indeed, we could not identify a satisfactory method of verifying assembly in an automated fashion.

The third laboratory assignment was related to mechatronics, with the goal of setting up the computer and Hapkit, including its microprocessor and circuitry, to enable haptic rendering. Students downloaded a template Arduino sketch, which included the code structure for performing haptic rendering with Hapkit. They then added lines of code to perform the following actions: (1) use sensor readings to compute the position of the Hapkit handle based on device kinematics and (2) compute the motor command required to generate a desired force. The data students submitted were measurements of their Hapkit performance recorded in the process of completing and testing their code. Answers were graded as correct if they were within a specified numerical tolerance of the expected answer. While these data did not verify correct implementation of code details, correct answers required that students had successful overall outcomes of their implementation.

The fourth laboratory assignment, in which students performed haptic rendering, is the main highlight of the course. Here, students used what they learned in the module lectures and quizzes to program four virtual environments: a virtual spring, damper, texture, and wall. For each type of virtual environment, students entered the range of the associated parameter (for example, virtual spring stiffness) that could be successfully rendered, and these data were automatically graded; correct answers had to be within a specified tolerance of the expected value.

The fifth and final laboratory assignment focused on rendering more complex virtual environments, which had a dependency on time. All students had to first render the sensation of "clicking" a click-top pen, followed by rendering a virtual environment of their choice. For the click-top pen, students entered several key simulation parameters successfully rendered, and these data were automatically graded; correct answers had to be within a specified tolerance of the expected value. For the second rendering, which was the students' choice, students in the guided course asked a friend to evaluate and comment on the realism of their rendering, and students in the MOOC selected from a set of given statements about how they perceived the realism of their renderings.

Results

Here, the results from using Hapkit in hands-on labs for both the guided course and the self-paced course are described. Data are based on precourse surveys, assignment submissions and grades, and a final postcourse survey. The use of these courses for research was approved by the Stanford University Institutional Review Board.

Guided Course

Course Demographics

A total of 99 people enrolled in the guided, five-week pilot course, which took place in the fall of 2013. The listed prerequisites included only high school-level physics and math, resulting in a range of education levels among those enrolled. Based on a survey given at the start of the course, there were 41.4% in high school, 20.2% in undergraduate studies, 16.2% in graduate school, 2.0% in professional school, and 20.2% not in school but, rather, working jobs in a variety of industries including education, health care, and design, to name a few.

Top Reasons for Enrolling

Students were asked in a postcourse survey about 10 different possible factors and the degree to which each one may have contributed to their decision to enroll in the course. For each factor, they could select one of five options (strongly agree, agree, neither agree nor disagree, disagree, or strongly disagree) to indicate its importance. Based on this rating scale, the three top contributing factors for the 82 (out of 99) students who responded were as follows: 1) I wanted to learn about haptics, 2) I wanted a course with some hands-on experience, and 3) I wanted to receive a haptic device (Hapkit), with 93.9%, 92.7%, and 87.8% of the students either agreeing or strongly agreeing for each of these factors, respectively.

Factors Contributing to Success

The overall completion rate of students who successfully finished the course and received a Statement of Accomplishment was 76.8%. When asked about the degree to which a variety of factors (shown in Figure 7) may have contributed to their success in the course, the top two factors, as measured on a five-point Likert scale, were 1) I had the opportunity to assemble the kit myself and 2) the class involved hands-on work. It is particularly interesting to see that the number one factor to which students attributed their success was not simply using Hapkit but actually the process of assembling it.

In addition to these self-reported reasons for success, we found that experience with three particular topics—kinematics, Lego Mindstorm, and physics—significantly correlated with students' final course grades. Correlation between these three factors and student grades had p values of 0.0065, 0.0336, and 0.0104, respectively, compared to nine other factors [Arduino programming, electronics, robotics (hardware), robotics (theory), haptic technology, soldering, shop tools, disassembling stuff, and fixing electrical appliances around the house] that did not show a statistically significant correlation.

Effectiveness of the Hands-On Component

Finally, students were asked a series of questions aimed at assessing the effectiveness of Hapkit and hands-on laboratory assignments. For the first set of questions, students were asked to assign a rating, from strongly agree to strongly disagree. As shown by the top six questions in Figure 8, students felt very strongly that Hapkit was helpful for learning hands-on skills, haptics, and physics concepts. They also thought that it was good for motivation and that hands-on activities helped them learn more.

As shown by the bottom six questions in Figure 8, students did not think that Hapkit was a distraction or that a computer

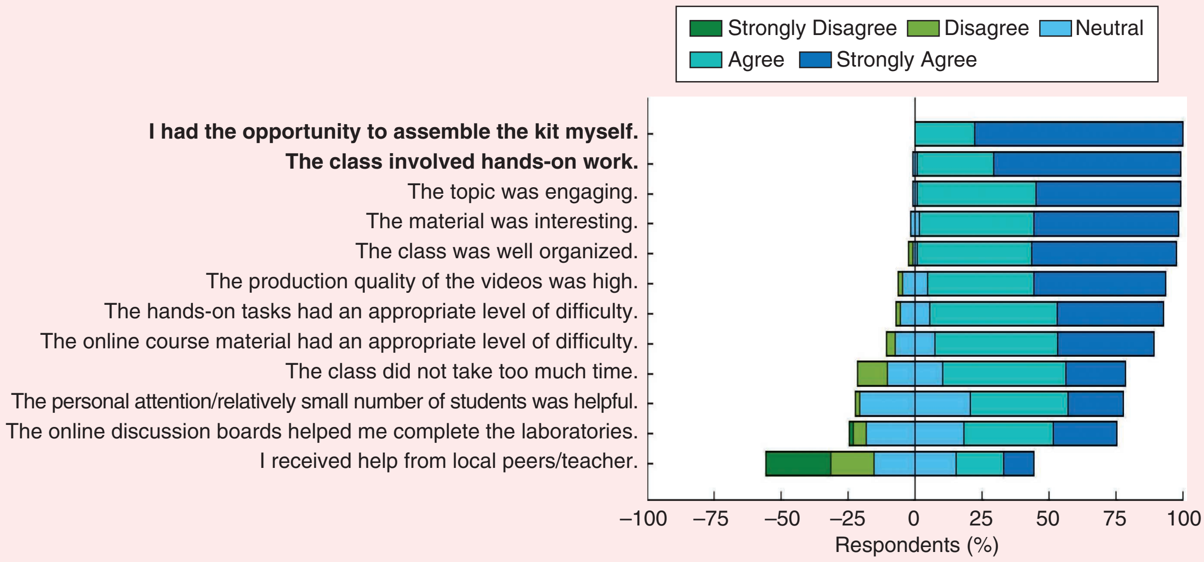

Figure 7. When students from the guided course were asked to rate (on a five-point Likert scale) potential factors contributing to their success in the course, the top reasons were 1) I had the opportunity to assemble the kit myself and 2) the class involved hands-on work. The line at zero represents the neutral point, where the percentages of respondents who agreed with the statement are shown to the right, and the percentages of those of those who disagreed are shown to the left.

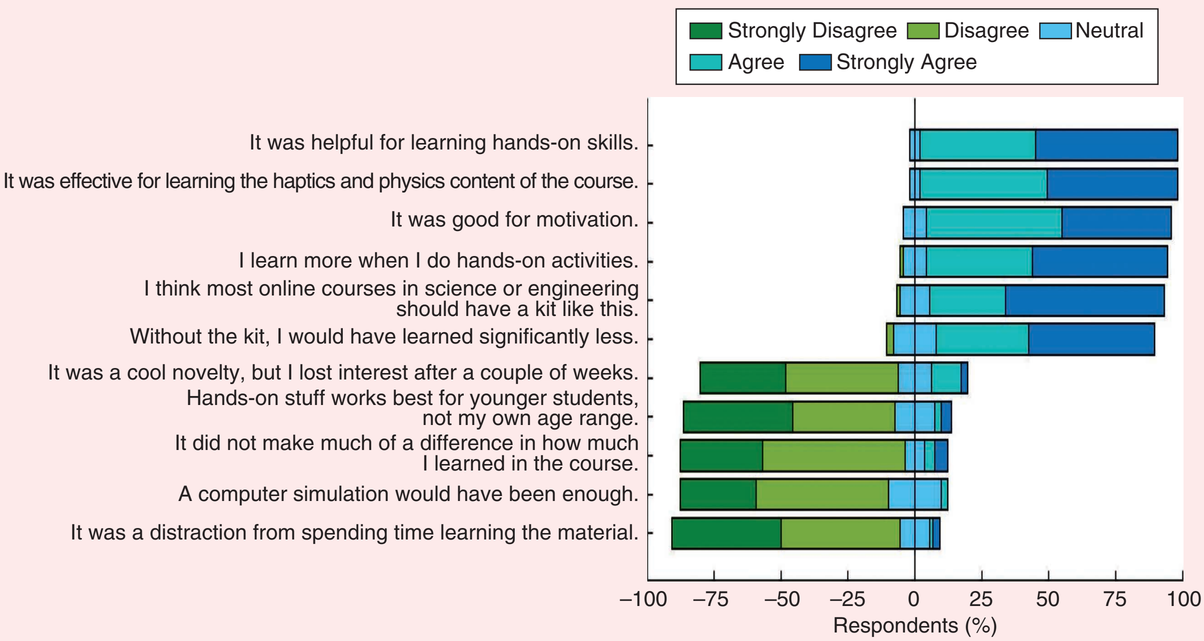

Figure 8. The questions to assess the effectiveness of the hands-on component of the guided course. Students were asked to rate each of the statements as either strongly agree, agree, neither agree nor disagree, disagree, or strongly disagree. The line at zero represents the neutral point, where the percentages of respondents who agreed with the statement are shown to the right, and the percentages of those who disagreed are shown to the left.

simulation would have been enough. In fact, when we asked more about the use of physical hardware, like Hapkit, compared to a computer simulation, we found that, on a scale from one to five (where 1 = Have Hapkit as part of the course, and 5 = Have some sort of computer simulation of Hapkit instead of physical hardware), the mean response was 1.56 ± 0.84, indicating a strong preference for the physical hardware. Students listed a variety of reasons for this preference, and many mentioned the difference between real-world systems and the approximations made in simulations. Comments included the following:

- "Computer simulations have limitations and can never be true, exact representations of something physical."
- "The kit gives the chance to feel real-world difficulties with electromechanical systems."
- "It made success an actual, tangible thing."

In addition, several students mentioned the importance of the physical interaction for learning and engagement. One student said, "I'm a more hands-on person; I learn more by engaging more senses." When asked how much they would be willing to pay (at most) for a Hapkit, only 8.6% said they would take it only if it were free, while 67.9% would pay US$1–50, 18.5% would pay US$50–100, 2.5% would pay US$101–150, and 2.5% would pay US$151–200. The current Hapkits cost approximately US$50 to make, so, with a few changes for large-scale manufacturing, Hapkits could be made and sold in a price range that would satisfy most users.

The final question assessing the effectiveness of integrating Hapkit into the course asked whether the physical kit made students think differently about online education. An overwhelming 92.6% answered "yes," perhaps illustrating a broader consequence of this hands-on online course. Student comments included the following:

- "The physical kit transformed this class from an online class to a real class. Strictly online classes are boring. This class was extremely engaging."
- "Online education has always had a reputation for being simple, quick, streamlined, and bare bones. However, the Hapkit introduced a new level of interaction and engagement to the subject matter."

Lessons Learned

Based on the survey results and general feedback, there were a few main lessons learned about hardware requirements for an online course. The first lesson was about the robustness and reliability of the kit parts. The final survey showed that 30.9% of the students had a hardware problem with their Hapkit at some point during the course. Of those issues, 43.5% were due to part of Hapkit breaking after assembly, 30.4% were caused by breaking a part while assembling, and 26.1% were attributable to a missing or broken part.

The particular part that was most commonly reported as broken was the force-sensitive resistor, which accounted for just under half of the hardware problems. This sensor was used only for a single part of an assignment and was not a component critical for Hapkit's functionality. Other hardware problems often involved the laser-cut acrylic pieces, which were either broken or had tolerances that were slightly off. It should be noted that, despite these few hardware problems, there was not a significant correlation between hardware issues and students' final course grades. Based on this first pilot course and the lessons learned, we updated Hapkit, as explained in the "Hapkit Device" section, and launched a self-paced MOOC.

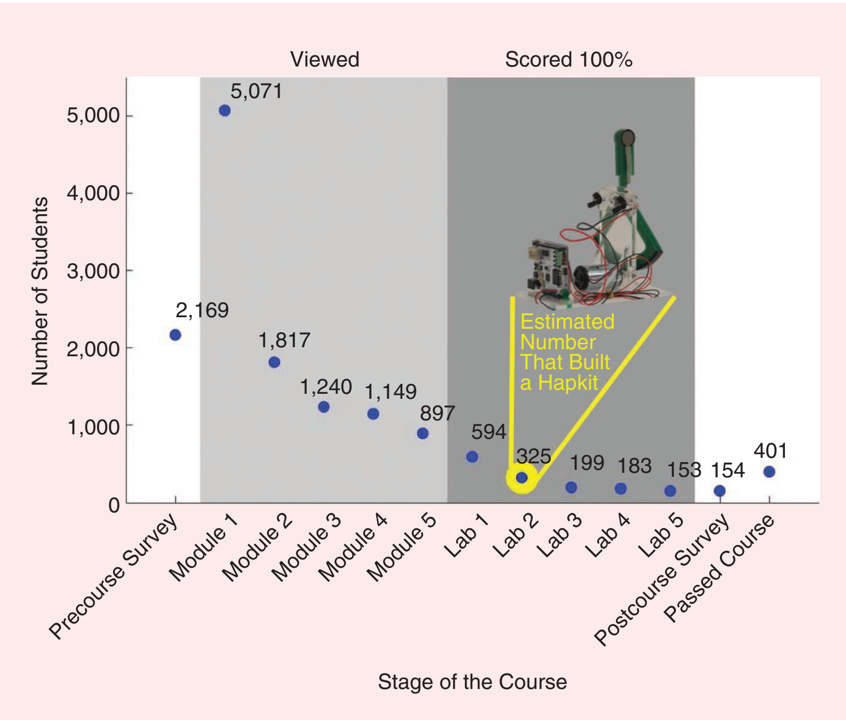

Figure 9. More than 7,000 people enrolled in the self-paced MOOC between 2014 and 2019. Here, we show the number of students at each of the following critical stages: completed the precourse survey, viewed a particular module (1 through 5), scored 100% on a particular lab assignment, completed the postcourse survey, and received a course certificate (Statement of Accomplishment).

The Self-Paced MOOC

To assess the success of the self-paced MOOC, it is important to define the number of students involved (and, therefore, responses received) at each stage of the course. Since the self-paced course, Introduction to Haptics, first launched in October 2014, a total of 7,062 students have enrolled. However, only a total of 2,169 students actually submitted the precourse survey. Figure 9 illustrates the number of students at each stage of the course, starting with completing the precourse survey and ending with receiving a final course certificate, or Statement of Accomplishment. The number of students who viewed a particular module as well as the number of students who scored 100% on a particular laboratory assignment is also shown. Despite the general trend of a slight decrease in module viewing and in perfect lab scores throughout the course, we can see that, after hardware was built in Lab 2, success in the labs remained relatively consistent throughout the remainder of the course.

Course Demographics

Demographic information, including current employment and gender, can be seen in Figure 10(a). This information is based on the 2,169 students who enrolled and filled out the precourse survey; due to the small numbers and lack of visibility on the plot, the four students who identified as gender nonconforming are not shown here. Interestingly, the majority of students were full-time employees, constituting just more than 40%. In addition to demographic information, Figure 10(a) shows the number of students within each category who passed the course by receiving a final grade of more than 50%, using overlaid colors.

Top Reasons for Enrolling

The precourse survey also included questions regarding students' decision to enroll in the course. Unlike a similar question given in the pilot course, which was designed specifically for that course and its unique hands-on structure, the questions here were from a standard survey for all Stanford online courses and were, therefore, more generic. Students were given 14 different possible reasons that may have contributed to their decision to enroll, and they were asked whether each item applied or did not apply to them. The three main top reasons were "general interest in the topic," "for personal growth and enrichment," and "for fun and challenge."

Effectiveness of the Course

For each of the five modules, Figure 9 shows the number of students who viewed that module as well as the number of students who received 100% on the laboratory portion of that module's assignment. Based on the number of students who successfully completed Lab 2, which required students to build a Hapkit and submit specific measurements based on what they built, we estimate that approximately 325 students tried to make their own Hapkit. We then estimate that approximately 199 of those students were successful in completing both the mechanical and electrical components, based on the number of students who received 100% on Lab 3, which required students to submit information on the forces they programmed and felt.

At the end of the course, students were asked to submit a postcourse survey. Although a total of 401 students successfully completed the course and earned a certificate, only 154 students filled out the postcourse survey. The remainder of the data in this section are based on the responses from this survey. For four topics important in the course, Figure 10(b) shows self-reported levels of knowledge both before and after taking the course. There was a general trend of increased

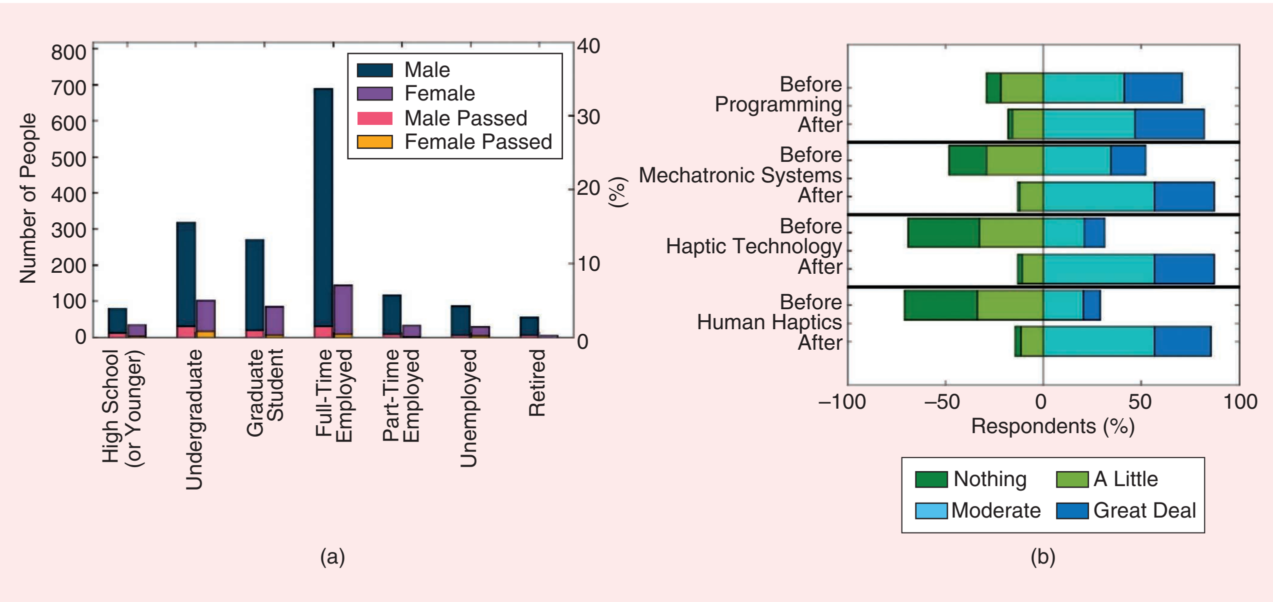

Figure 10. (a) The total numbers and percentages of students who enrolled and completed the precourse survey for the self-paced MOOC, based on gender and current employment. Overlaid on each category is the number of students in that category who passed the course. Due to the small numbers and lack of visibility on the plot, the four students who identified as a nontraditional gender are not shown here. They fell into the categories of graduate student, full-time employed, and part-time employed. (b) Self-reported levels of knowledge on four topics (programming, mechatronic systems, haptic technology, human haptics) before and after the self-paced MOOC, where responses shown on the left half represent knowing nothing to a little and responses on the right half represent knowing a moderate amount to a great deal.

knowledge from before to after for all topics. Out of the four areas, students showed the smallest increase in programming knowledge, possibly due to starting with higher levels of knowledge in this area, compared to the other three. The largest difference was seen when comparing how much students reported knowing about human haptics and haptic technology before versus after the course.

There was overall satisfaction with the amount students felt they learned, and an overwhelming majority said the physical kit made them think differently about online education.

In addition to reflecting on the various topics learned in the course, students were asked a series of questions about their overall satisfaction. Responses were given on a scale from 1 to 7, where 1 represents extremely unlikely/dissatisfied, and seven represents extremely likely/satisfied. When asked how likely or unlikely they were to take another course with the same format, the mean was 5.53 ± 1.4, demonstrating overall satisfaction with the course format, including the hands-on components. Students were also very satisfied with the amount they learned in the course (5.63 ± 1.19) and even said they would likely pursue the topic further after having taken the course (5.61 ± 1.31).

Lessons Learned

The main lesson learned from offering this self-paced, hands-on MOOC is the importance of readily available hardware for students. Unlike in the guided course, where we sent students all of the parts needed to build their own Hapkit, students in the self-paced course were given instructions on where to purchase each kit item, but they had to do so themselves. As a result, only 51.64% reported in the postcourse survey that they successfully built and used a Hapkit in the labs. Most of the comments about ways to improve the course revolve around making Hapkit available either as a prebuilt device or as a complete kit, making it easier for students to do the labs. There were also numerous comments that making Hapkit commercially available would help international students in particular, since many of the components were difficult to obtain outside the United States.

Discussion and Conclusions

A new low-cost, open source, easy-to-assemble haptic device, called *Hapkit*, was designed and used in two variations of an online course. The first was a five-week, instructor-guided course, where the components of Hapkit were physically sent to each student, ensuring they had all materials necessary to build the device. The second course was a self-paced MOOC, where students were required to purchase the components themselves to build the kit. Both courses had the same set of learning objectives and were aimed at filling the void in hands-on laboratories for online engineering courses.

The overall results and feedback about the hands-on laboratories were positive, motivating further development in this area. Students reported that assembling the kit themselves and having hands-on laboratories contributed to their success in the course. They also indicated a strong preference toward the physical hardware rather than a computer simulation. Finally, there was overall satisfaction with the amount students felt they learned, and an overwhelming majority said the physical kit made them think differently about online education.

There are some notable differences in demographics and completion percentages between the guided course and the self-paced MOOC; at the same time, there are similarities. For example, building Hapkit appears to be related to successfully completing the course. The 76.4% completion rate in the guided course is far higher than the average completion rate in a typical MOOC (though this is a somewhat unfair comparison because our course had a limit on the number of students who could enroll and was therefore not truly "open"). In the self-paced MOOC, building or attempting to build Hapkit is highly predictive of completing the course.

Although it is not possible to assume a causal relationship between assembling Hapkit and succeeding in the course, the strong relationship between them—even if that relationship is caused by a latent factor like motivation, investment, or dedication—is provocative. Koller et al. [18] showed that students who paid a small amount to receive a certificate in a MOOC had a 74% completion rate, while students who did not had only a 9% completion rate. This number is quite close to the 76.4% of students who completed the guided course, where the students were given, but did not pay for, the hardware.

Based on the lessons learned about hardware requirements in an online course, a number of changes have since been implemented [19]. Hapkit 3.0 has been designed to be fully 3D printed, enabling more students to fabricate and build their own. In addition, an easy-to-assemble capstan transmission has been designed to ensure high performance, even with inconsistencies in the 3D printed parts. This latest version of Hapkit is now being used in a new instantiation of the online course, available on EdX: http://hapticsonline.class.stanford.edu. Finally, the newest design allows for customization of the handle by each student to help promote excitement and ownership.

Based on the success of Hapkit, additional open source devices have since been developed [20]. The first, called *Graphkit*, uses two standard Hapkits with a few additional components to form a pantograph mechanism, which can be used as a programmable drawing tool. The second, called *Haplink*, connects two Hapkits in series to form a 2-DoF mechanism. The goal of the entire family of Hapkit devices is to enable accessible, hands-on laboratories in online settings as well as to understand the role of haptics in education.

The methods developed for and lessons learned from teaching online haptics courses for the public have been put to use at Stanford University for online teaching during the COVID-19 pandemic. In spring 2020, we developed a system to allow students in an online graduate class to remotely teleoperate each other's Hapkits, providing a unique physical connection between students and instructors as well as (we hypothesize) enhancing engagement. Students were able to accomplish this using the standard Arduino programming integrated drive electronics and Python code, all freeware, and minimal understanding of home router settings and firewall adjustment.

At the end of an unprecedented quarter of online learning at Stanford, students used their Hapkits to perform remote "handshakes" on the last day of class. There has been an increased interest in using Hapkit for both in-person and remote teaching of a variety of courses at different universities. Long term, we plan to analyze the use of Hapkit and any trends in participation in our MOOC during and after the current pandemic. Future work will include an analysis of the data across the years with the goal of better understanding how world events may affect student participation.

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