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3-D Printed Haptic Devices for Educational Applications*

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***Abstract*— Haptic technology has the potential to expand and transform the ways that students can experience a variety of science, technology, engineering, and math (STEM) topics. Designing kinesthetic haptic devices for educational applications is challenging because of the competing objectives of using low-cost components, making the device robust enough to be handled by students, and the desire to render high fidelity haptic virtual environments. In this paper, we present the evolution of a device called "Hapkit": a low cost, one-degree-of-freedom haptic kit that can be assembled by students. From 2013-2015, different versions of Hapkit were used in courses as a tool to teach haptics, physics, and control. These include a Massive Open Online Course (MOOC), two undergraduate courses, a graduate course, and a middle school class. Based on our experience using Hapkit in these educational environments, we evolved the design in terms of its structural materials, drive mechanism, and mechatronic components. Our latest design, Hapkit 3.0, includes several features that allow students to manufacture and assemble a robust and high-fidelity haptic device. First, it uses 3-D printed plastic structural material, which allows the design to be built and customized using readily available tools. Second, the design takes into account the limitations of 3-D printing, such as warping during printing and poor tolerances. This is achieved at a materials cost of approximately US $50, which makes it feasible for distribution in classroom and online education settings. The open source design is available at `http://hapkit.stanford.edu`.**

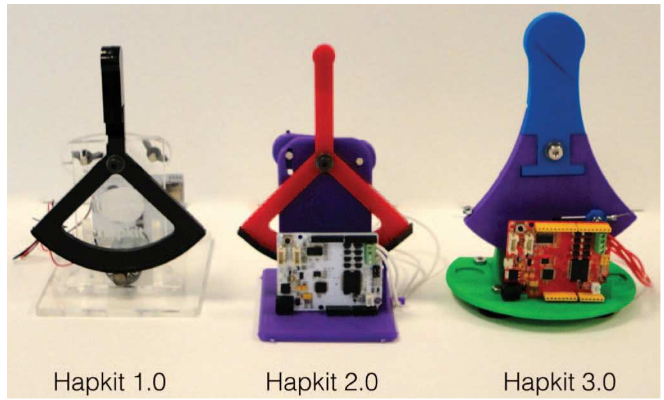

Fig. 1. Three versions of low-cost, single-degree-of-freedom haptic devices for education: Hapkit 1.0 was designed in 2013 and uses a friction drive and laser-cut acrylic structural elements. Hapkit 2.0 was designed in 2014 and uses a friction drive and a combination of acrylic and 3-D printed plastic structural elements. Hapkit 3.0 was designed in 2015 and uses 3-D printed plastic structural elements.

I. INTRODUCTION

A. Motivation

Hands-on educational activities help students understand abstract concepts by connecting mathematical models to physical interactions in a manner that exploits students' intuition and experiences with the physical world. A haptic device provides a versatile, flexible, programmable interface capable of simulating a wide range of environments, and has the potential to expand and transform the ways that students experience a variety of science, technology, engineering, and math (STEM) topics. Robotics is already a popular tool used in STEM education, and we believe that haptics has even greater potential for learning because it is inherently designed for interaction and display of information. Haptic technology for education also facilitates fundamental research related to hands-on learning, including cognitive embodiment, the role of physical experiences in understanding physics concepts, and the influence of hands-on labs on engagement and retention.

There are open questions about how to best design haptic devices for educational environments. Some past work points to enhanced learning with haptics [1]–[7], while other results do not support this conclusion [8]–[10]. These studies agree that haptic feedback engages students, but disagree on the effect of haptics on learning. Minogue et al. [9] found no difference in learning with and without haptic feedback, although haptic feedback aided low achieving students in answering open-ended questions about learned concepts. Jones et al. [1] found that students who were given haptic feedback were able to recall more lesson concepts than those who did not receive it. However, Moore et al. [10] found that haptic augmentation contributes little to learning, and may even inhibit learning. These studies vary widely in concepts taught, software, and type of haptic device used, from commercial 3-degree-of-freedom (3-DOF) devices to custom 1-DOF devices [11]–[13].

We propose that haptic device design significantly affects the practicality of educational use in terms of performance, cost, robustness, and distribution, as well as learning outcomes. In this paper we address haptic device design considerations relevant to practical implementation of kinesthetic haptic feedback in educational environments. Specifically, we describe the evolution of our Hapkit series of educational haptic devices (Figure 1).

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B. Prior work

One of the first haptic devices designed specifically for education was the Haptic Paddle, developed at Stanford University in the mid-1990s [7], [11] for use in an undergraduate dynamic systems laboratory. The Haptic Paddle is a kinesthetic 1-DOF haptic device that uses a capstan drive for transmission. Many other groups have iterated on this design and used their own implementations in educational environments, typically undergraduate engineering courses [4], [12]–[17]. These educational haptic devices vary in materials, transmission method, actuation, sensing, user interface, microprocessor, cost, and performance. One notable change in many devices from the original Haptic Paddle is the transition from a capstan drive to a friction drive for the transmission [13], [16], [18], which sacrifices haptic performance for ease of assembly and maintenance.

Most of these devices were designed primarily to be used as laboratory equipment in courses using dedicated and stationary computers, data acquisition boards, power supplies, and motor amplifiers. Control software has been implemented using a wide variety of programming environments such as industry-grade software tools, custom software written in C++, as well as Matlab and Simulink interfaces [13], [16]. Recently, the availability of low-cost, open source microcontroller-based kits such as the Arduino family of devices has enabled groups to build educational haptic devices that are less costly and more modular and portable. We worked with Seeed Studio (Shenzhen, China) to develop a board based on the Arduino Uno, with additional integrated amplifier and sensing circuitry, called the Hapkit Board [18]. Other groups such as Haply [17] have recently used the Hapkit Board to build other low-cost haptic devices. The use of the Hapkit Board as well as other design changes enabled our group to develop a series of haptic devices with an emphasis on design for wide distribution.

In addition to kinesthetic haptic devices, vibratory and variable friction touchscreens have also been used in education [19], [20]. The educational uses of these tactile devices included teaching mathematical functions to visually impaired students and workshops where students program their own tactile applications.

C. Contributions

In this paper, we present the evolution of a device called "Hapkit": a low cost, 1-DOF haptic kit that can be manufactured and assembled by students (Figures 1 and 2). The Hapkit was first developed in 2013 as a low-cost version of the Haptic Paddle, to be used in a Massive Open Online Course (MOOC) on the topic of haptics. During the following two years, we evolved the design in terms of its structural materials, drive mechanism, and mechatronic components.

The aim of this paper is to disseminate lessons learned in the design and implementation of inexpensive 3-D printed haptic devices, through a description of the iterative process of Hapkit development and its use in various educational environments. This work is relevant for readers interested in designing inexpensive haptic devices as well as using haptics in educational applications. While analysis of learning outcomes from the use of Hapkit is a long-term goal of this work, here we focus on issues of practical implementation, performance, and use by students.

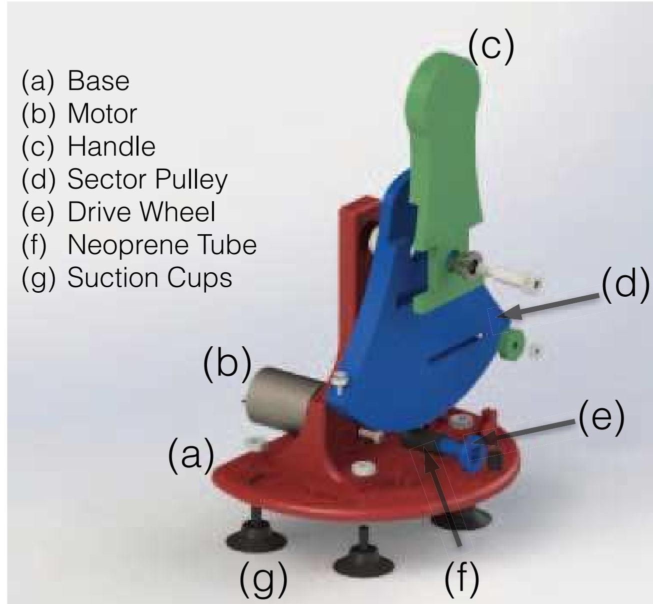

Fig. 2. Diagram of Hapkit 3.0, depicting the main components shared among all Hapkits: base, motor, handle, sector pulley, and drive wheel. Hapkit 3.0 also includes a neoprene tube and suction cups.

II. DESIGN GOALS FOR 3-D PRINTED HAPTIC DEVICES

Our design goals for 3-D printed haptic devices are generated from (1) kinematics and rendering requirements, (2) manufacturing and assembly requirements, and (3) lessons learned from the implementation of Hapkit 1.0 [18].

A. Kinematics and Rendering

There were several features of the Haptic Paddle and original (acrylic) Hapkit 1.0 that we sought to re-create in a 3-D printed Hapkit. A 1-DOF device limits cost and complexity, and our experience with undergraduate and graduate lessons in controls, dynamics, and haptics has demonstrated that a 1-DOF device is sufficient to simulate physics and dynamics concepts such as springs and dampers [7], [13], [14]. A 1-DOF haptic device can also be used to simulate sinusoids or other mathematical functions by using force at the handle as an output and position or time as an input – this enables the user to "feel" two-dimensional functions. In past devices, the joystick-like shape was found to be intuitive for users and easy to grasp for a range of hand sizes. The kinesthetic (as opposed to tactile) haptic design approach is advantageous because of the relatively large scale of motions and forces possible. In addition, rotational motion of the device is desirable because the alternative, linear motion, requires sliding mechanisms that usually result in high friction. We have found in previous devices that it is acceptable to display nominally linear systems along the large-radius arc traveled by the handle.

We aim to develop devices that are of the impedance type, such that users input position and the device outputs force corresponding to a rendered impedance or nonlinear force-displacement relationship. This requires the device to be backdrivable, indicating the need for transmission with minimal friction and moving parts with low inertia. In addition, the motor – typically one of the most expensive components in a kinesthetic device – should have low friction and inertia, as well as low cogging torque. (Our goal was to use off-the-shelf components where possible, but high performance at low cost can also be achieved using custom motors, such as the electromagnetic actuation system used in [15].) Similarly, the transmission system should provide a consistent feel throughout the workspace. We aim for a device with a maximum force output of approximately 5N and a maximum stable stiffness on the order of several hundred N/m, which provides a sufficient range of forces and stiffness to display a wide array of compelling virtual environments while keeping the maximum force low enough to ensure users' safety [21]–[24]. Related to this requirement is the need for high-resolution position sensing, accurate torque output, and the ability to close a haptic control loop at a rate of at least several hundred Hz. While not all of these goals have been numerically quantified for the Hapkit series of devices, generally we want the Z-width [25], [26] to be as large as possible, while respecting constraints of cost and ease of assembly.

B. Manufacturing and assembly

An important goal for designing the Hapkit series of devices is that students and educators without engineering expertise should be able to obtain or make the parts using commonly available tools and online purchasing. (This emphasis could become less important in the future if such educational devices become commercially available.) In addition, we wanted to design devices that students could assemble themselves. This design requirement is fundamental to the idea that Hapkit is a "kit" – we propose that students will learn more by assembling the device themselves. In particular, students may have a better understanding of rendering algorithms with knowledge of the device kinematics obtained through the assembly process. Design for assembly means that the device should be comprised of a minimal number of parts and that the assembly process should be easy to explain and robust (i.e., parts should not break while being assembled, and students should not be able to assemble the device in the wrong way). Finally, we aim for the device to be "open", such that students can see various parts of the device moving and interacting during use.

C. Lessons learned from Hapkit 1.0

The starting point for designing 3-D printed haptic devices was Hapkit 1.0, which was created in 2013 at Stanford University with the aim of being used in a new MOOC on haptics [18]. In this MOOC, Hapkit 1.0 was used as a tool to teach haptics through kinematics, mechanics, and programming of force/torque relationships to simulate various virtual environments. The students also learned mechatronics through the functionality of the Hapkit Board and how to program it. In order to accommodate the diverse demographic of the online course and enable students to build the entire device without in-person instruction, several major design changes were made to the original Haptic Paddle, inspired by similar changes made at Vanderbilt University [13].

First, the drive mechanism was changed from capstan drive to friction drive, because the tensioning of the cable in a capstan drive is known to be a tedious and difficult procedure for novices. Thus, ease of assembly was chosen over the decrease in performance resulting from the friction drive. Another advantage of the friction drive was that, when the system became unstable due to programming/rendering errors, the motor's Drive Wheel and Sector Pulley would lose contact and the motor could (ideally) spin harmlessly. A height adjustment bar was added in order for students to adjust the friction in the transmission after they assembled the device. Second, as described in Section I-B, a low-cost, custom circuit board based on the Arduino Uno was designed. This Hapkit Board can be programmed using the Arduino Integrated Development Environment (IDE) and includes additional features such as two motor driving circuits, an integrated position sensor (magnetoresistive sensor), and an SD card reader. Finally, Hapkit 1.0 was primarily made out of laser-cut acrylic pieces, with corresponding tabs and slots for connecting pieces. Two pieces, the Drive Wheel and a holder for the magnet used with the magnetoresistive sensor, were made with a ProJet 3-D printer (3D Systems). These pieces were glued onto each side of a dual-shafted Maxon AMax 26, which was obtained as a surplus item at a very low cost (albeit with limited availability).

Although Hapkit 1.0 addressed several of the needs for a device for online learning, it highlighted a number of remaining design challenges. In the 2013 online course, all of the Hapkit components were obtained by the instructors and mailed to the students, a practice that would not be sustainable for a larger MOOC (only 100 students were enrolled in the first offering). To enable the students of future classes to manufacture the components themselves, the acrylic pieces would have to be replaced, since very few students have access to a laser cutter. The initial online course also revealed the need to reduce the total number of parts required, ensure that pieces could not be assembled upside-down or backwards, and enable students to easily build replacements for broken parts. The final challenge was to reduce the overall cost of the remaining components, especially the high-quality Maxon motor.

III. HAPKIT 2.0: A 3-D PRINTED DEVICE USING A FRICTION DRIVE

Hapkit 2.0 built on the lessons learned from Hapkit 1.0, and was used in several educational environments, including a Haptics MOOC, university courses, and a middle school class. We focus our discussion below on changes from the

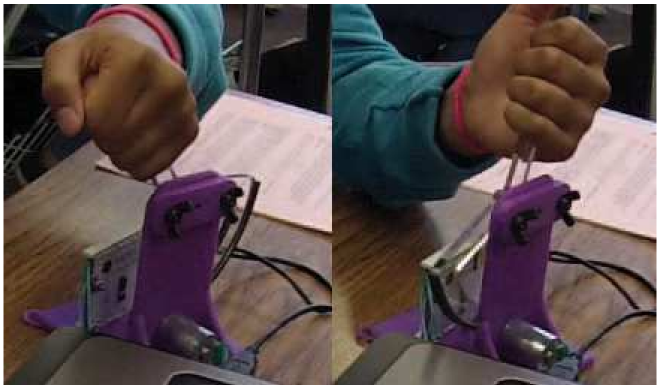

Fig. 3. A student in middle school workshop moved the Sector Pulley back and forth to feel a virtual spring with Hapkit 2.0.

existing Hapkit 1.0 and the impact of the design and challenges observed in educational use. The Stanford University Institutional Review Board approved the MOOC and middle school workshop studies, and informed consent or assent was obtained from subjects.

A. Hapkit 2.0 design process

In order to widely disseminate Hapkit, students needed to be able to manufacture or buy all the parts for themselves. Given the increased accessibility of low cost 3-D printers, we aimed for Hapkit 2.0 to use structural components made on a widely available 3-D printer, the MakerBot Replicator 2, using PLA material. The 3-D printing process allowed us to design Hapkit 2.0 with a reduced number of parts compared to Hapkit 1.0. The 3-D printed Base was a single piece that included supports to screw in the Hapkit Board and Sector Pulley, in contrast to 6 different pieces that needed to be glued together for Hapkit 1.0. The Sector Pulley was also intended to be a single 3-D printed piece instead of 3 laser-cut pieces. The Drive Wheel and Magnet Holder pieces of Hapkit 1.0 were fused together into one piece that attached to the shaft of a $3.49 Mabuchi DC motor (purchased from Jameco).

However, the poor quality of 3-D printed parts was a limiting factor. The 3-D printed Drive Wheel was not smooth enough for a consistent friction drive transmission. Thus, we added a piece of neoprene tubing to surround it. This enabled consistently smooth contact between the neoprene tube on the Drive Wheel and a neoprene strip mounted on the edge of the Sector Pulley. In addition, the 3-D printed Sector Pulleys were usually slightly warped, resulting in circular arcs with eccentricity of greater than 1 mm. This small eccentricity resulted in the Drive Wheel not maintaining friction contact with the Sector Pulley throughout the workspace of the Hapkit. We tested the design of the 3-D printed Sector Pulley with several low-cost 3-D printers including the MakerBot Replicator 2, Flashforge Creator, and Afinia H480 – none of which were able to print a sufficiently circular Sector Pulley. This meant that the Sector Pulley had to still be laser cut in Hapkit 2.0 (Figures 1 and 3).

B. Observations from use in Haptics MOOC

In 2014 we launched a *self-paced* Introduction to Haptics MOOC which covered the same topics as our previous MOOC. This course has had over 4,000 students enrolled, ranging from elementary school students to graduate students to professionals. In contrast to the 2013 course, we did not distribute Hapkits to the students – they had to obtain the parts on their own, following instructions online. Students had significant challenges implementing Hapkit 2.0. Different 3-D printer software packages interpret STL files differently, and as a result, some students found that their printers created the device in the wrong orientation. Especially on lower quality 3-D printers, this caused much of the detail of the part to merge into the support material and make part removal impossible without damaging the component. Another problem we encountered was that students did not know the target "feel" that should result from moving the height adjustment bar. Remotely it was very difficult to explain to students what the right amount of friction should be. Also, due to the fact that PLA plastic is more compliant than acrylic, the correct height adjustment was harder to attain in Hapkit 2.0 than in Hapkit 1.0.

The attachment of the Hapkit Board was also problematic. In Hapkit 1.0, laser cut pieces allowed students to screw the Hapkit Board to the base in three locations that were easily accessible. In Hapkit 2.0, the locations of these holes were inconsistent due to the poor tolerances of the 3-D printing process. This inconsistency, compounded by the fact that there is little room to work with when screwing the Hapkit board to the base, made it very hard to secure the Hapkit Board to the Base. The need for a laser-cut Sector Pulley introduced an impractical manufacturing requirement for most students. Students who had no access to a laser cutter attempted to 3-D print the Sector Pulley, which was typically unsuccessful. Some students opted for altering the design since the friction drive was not working for them and posted on the course discussion board designs with other transmissions including gears. The main lesson learned from Hapkit 2.0 was the need for a more thorough redesign of the Hapkit for assembly and 3-D printing, taking into account warping and inconsistency between prints.

C. Observations from use in university classes

Hapkit 2.0 was also used in two Stanford University classes: a 16-student Freshman specialty course on haptics with topics paralleling those of the MOOC, and an 80-student introductory controls course. In the Freshman course, students had to assemble Hapkits themselves, but were given all components except for the 3-D printed parts. They were asked to use existing STL files/CAD drawings to 3-D print and laser-cut the necessary parts using Stanford-owned machines. With the active assistance of the teaching staff, all 16 students were able to create functional Hapkits. However, throughout the use of the Hapkit 2.0s in this class, the instructors had to re-set the height adjustment bars when the transmission resulted in either too much or too little friction. It was clear that the novice students could not determine this adjustment on their own without the instructors demonstrating physically what it *should* feel like. A positive outcome of the Hapkit 2.0 design was that the Freshmen were able to make significant mistakes in programming rendering algorithms on their Hapkits, and the resulting instability did not typically damage the Hapkits because of the friction drive's capability to lose transmission contact when the motor began spinning uncontrollably.

In the controls course, taken mostly by senior undergraduates and first-year graduate students, Hapkit 2.0 was used quite differently. Several Hapkits were set up as laboratory demonstrations connected to Simulink models to show students the effects of PID and lead/lag controllers, as well as frequency response of the system. As 80 students rotated through the hands-on demonstrations, the Hapkits suffered significant damage due to the frailty of the 3-D printed parts. Failure modes included broken motor drive-wheels, slipped height adjustment bars, and motors shifted in their mounting holes. Because the demonstrations were left accessible to the students at all times, and the students were not always aware when a Hapkit was broken, there is a significant concern that some students felt poor/incorrect haptic demonstrations of the controllers. This level of damage was not observed in the Freshman course, where each device was owned by an individual student, possibly resulting in greater care taken with the device, as well as reduced usage time.

D. *Observations from use in a middle school classroom*

Over two weeks in May 2015, we ran a pilot workshop using Hapkit 2.0 in a middle school classroom with 32 students. The course was a modified version of our MOOC and Freshman course in which students were given a brief introduction to haptics and how the Hapkit works, and were aided in rendering a spring, a damper, and a texture. Facilitators brought assembled Hapkit 2.0s to the classroom for several hours each day, and students worked together in groups of two with a single Hapkit.

The middle school environment introduced many challenges beyond the university classes and MOOC described above. One difficulty was the use of a regular classroom. The classroom desks were slanted and slippery, and a large number of extension cords and power strips were required to route power to all the desks in the room. In addition, the younger student population stressed the mechanics of the device in ways we had not seen from older students, including: knocking the Hapkit onto the floor, breaking thin pieces of 3-D printed material attaching the Hapkit Board to the base, and applying too much pressure to the motor shaft by pushing down on the handle. The latter caused the 3-D printed motor's drive wheel to shear off the motor shaft, which is very difficult to notice and debug; even if the Drive Wheel is not consistently attached to the motor shaft, as the motor spins it can still spin the Drive Wheel some amount. We also noticed that the height adjustment bars had to be re-set often. This would be an impossible task for novices at the middle school level, indicating that such a workshop could not be run without expert facilitators present.

During the middle school workshop we recorded video and audio of three pairs of students as they learned to program the Hapkit to render the virtual spring (Figure 3). The students were tasked with modifying the value of the spring constant in the code and feeling the change in the haptic feedback. In our video analysis, we focused primarily on the students' interactions with the Hapkit in order to gain a deeper understanding of how the Hapkit's design interacted with the realities of the classroom. We learned that many aspects of the Hapkit design fit naturally into the classroom context, feeding the students' curiosity and guiding them towards the completion of their task, but some aspects caused confusion.

All three groups analyzed initially followed the same path and encountered the same obstacles, but all three ended the workshop in different places. They were all initially curious about the Hapkit, spending minutes examining the different components and their relationships to one another. We see this as a vindication of the open design of the Hapkit. If we had chosen to hide the circuit board and motor inside a black box, the students would not have had the opportunity to explore the device in the ways that we observed. The students were highly engaged when the Hapkit correctly rendered the virtual spring, spending a significant amount of time moving the Sector Pulley back and forth. And even when the code was incorrect, the friction drive allowed the Hapkit to fail gracefully. In this case the vibrating Sector Pulley acted as an alarm that quickly alerted the facilitators. However, in one case this behavior led to confusion given the nature of the task (to render a spring). We also recorded one instance on video (and multiple instances not on video) of the Sector Pulley and Drive Wheel not interacting correctly, leading to lengthy repairs that spoiled students' chances of experiencing the virtual spring.

All three pairs of students uploaded malformed code that caused their Hapkits to misbehave and only one pair of students successfully rendered a virtual spring. Due to this high failure rate, for the other two environments (damper and texture), we made sure to implement a more robust uploading process so that malformed code would not be used and students were able to render those environments successfully with help from the facilitators. However, the problem remained that a software failure would lead to a mechanical one, and students were not able to easily distinguish a working Hapkit 2.0 from a broken one. These observations directly informed many of the changes that were made in Hapkit 3.0.

IV. HAPKIT 3.0: A 3-D PRINTED DEVICE USING A CAPSTAN DRIVE

A. *Design process*

Hapkit 2.0, although intended to be more accessible for students, was limited by the high tolerances needed for a good friction drive transmission. With components and materials less robust than Hapkit 1.0, the friction drive required a haptics expert to put it together successfully. The next design, Hapkit 3.0, was designed specifically for 3-D printing, with a more robust transmission and assembly process. Hapkit 3.0 uses the Hapkit board developed for Hapkit 1.0 and can output a maximum force of 6N. Its maximum travel distance is of 12 cm. The maximum travel distance can be increased or decreased by customization of the handle. In this section, we describe the main design changes to the Base and Sector Pulley. Figures 2 and 4 show the Hapkit 3.0 assembly and components.

1) 3-D printed Sector Pulley and Capstan Drive: For the transmission of Hapkit 3.0 we revisited the capstan drive used in the original Haptic Paddle. We eliminated the capstan drive in Hapkit 1.0 because of the perceived difficulty of assembling and maintaining typical capstan assemblies by students. Here, we focused on making the capstan drive easier to assemble and more robust to avoid unwinding when the device becomes unstable [27], [28].

A robust capstan transmission requires a tightly wound cable. In the original Haptic Paddle, the cable is attached at each end of the Sector Pulley and one end of the Sector Pulley acts as a flexure. However, the PLA plastic used in 3-D printing is too brittle for this design. To allow tightening of the cable, we incorporated a slot with a fastener (Figure 5d) to help the user to tension the wire. In order to prevent the cable from unwinding by slipping off the end of the capstan, Hapkit 3.0 has a slot at the bottom of the sector pulley to guide the cable (Figure 5b) and a stop at the end of the motor shaft that is two times larger in diameter than the capstan (Figure 6c). The neoprene tube on the capstan also compresses as the cable is tensioned, adding friction and preventing unwinding and slipping.

Hapkit 3.0's Sector Pulley incorporates design features which make it easy to assemble. It has Cable Routing features (Figure 5e), a Cable Guide (Figure 5b), and a Cable Attachment Screw (Figure 5c), which help keep the cable in place as the Hapkit is assembled. A Pre-Loading feature

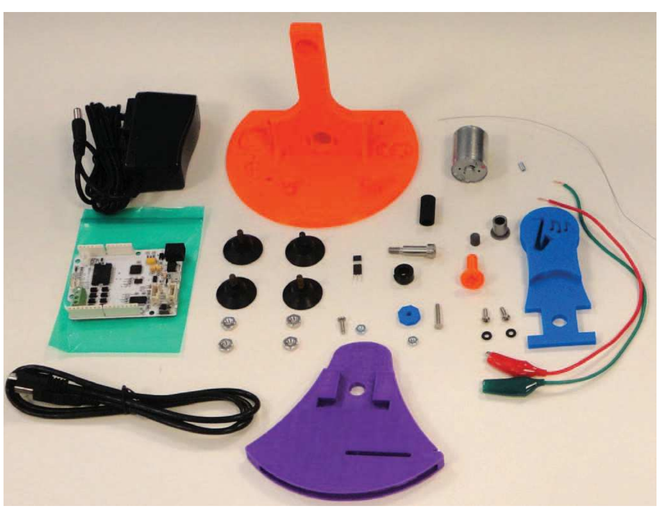

Fig. 4. Hapkit 3.0 assembly parts: Hapkit 3.0 is made from 3-D plastic structural material and readily available electronic and hardware components.

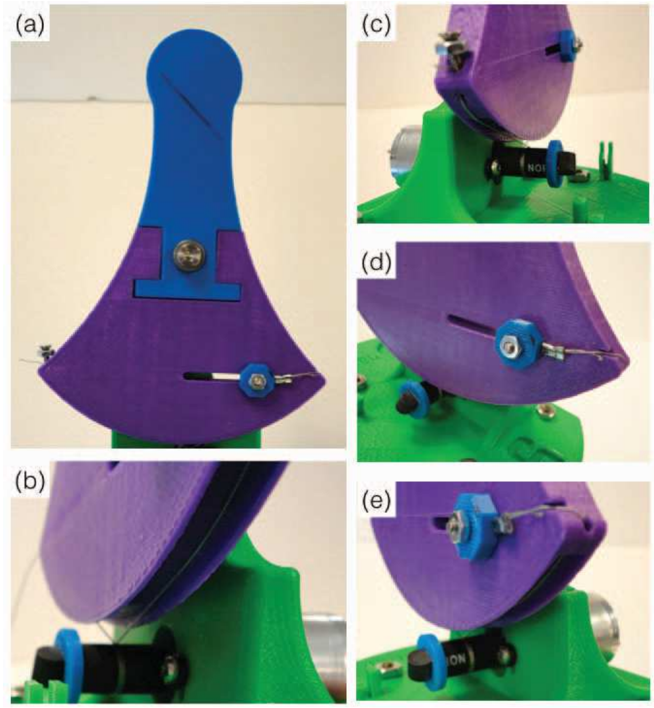

Fig. 5. Hapkit 3.0 Sector Pulley features: (a) Sector Pulley (b) Cable-Guide (c) Cable Attachment Screw (d) Pre-loading Feature (e) Cable-Routing Features.

(Figure 5d) keeps the necessary cable tension.

We also now take advantage of the potential for customization/personalization enabled by 3-D printing. We designed the Hapkit 3.0 Sector Pulley in two parts. The drive part of the Sector Pulley is fixed and optimized, but the handle can be customized by students using free software such as Google Sketchup. The handle snaps onto the drive half of the Sector Pulley (Figure 5a) without additional hardware.

2) 3-D printed Base: Hapkit 3.0's Base design is optimized for 3-D printing and robustness. We replaced the screws that held the Hapkit Board with slots that fit the Hapkit board so it can slide in and snap into place (Figure 6b). This eliminates extra parts and improves assembly time and robustness.

In Hapkit 1.0 and 2.0, it is expected that the user will hold onto the Hapkit's base with the non-dominant hand and then grab the paddle with the dominant hand when feeling virtual environments. Users can forget to do this, resulting in poor haptic feedback (because the base moves away from the dominant hand when forces are applied) and even worse, the potential for the device to fall off the table (as was seen in the middle school classroom). Thus, we added suction cups to the base (Figure 6d), a design addition inspired by work at Colorado School of Mines [29].

Hapkit 3.0's design also incorporates a Motor Support (Figure 6e) that helps the user center the motor and keep it in place as it is being attached to the base. In addition, Hapkit 3.0 has a larger hole for the motor shaft (Figure 6f) which prevents rubbing of the Drive Wheel's neoprene against the Base, even if the motor is not perfectly centered

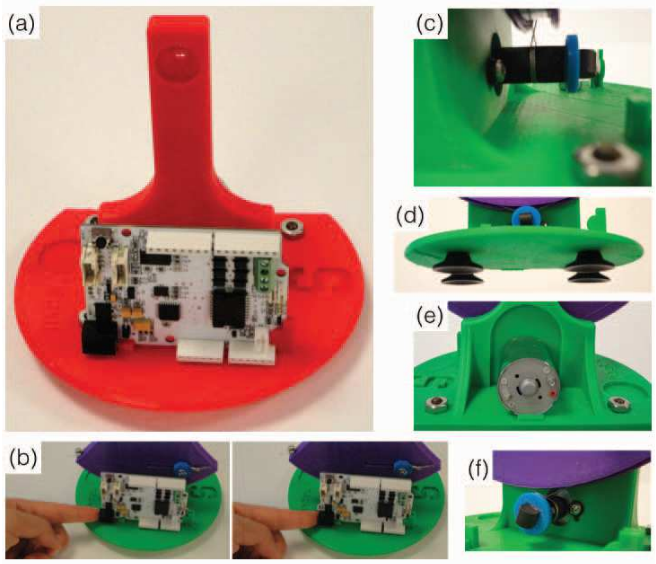

Fig. 6. Hapkit 3.0 Base features: (a) Base (b) Board Snap-Fit (c) Drive-Wheel (d) Suction Cups (e) Motor Support (f) Motor Shaft Hole.

after assembly. In order to optimize the design of Hapkit 3.0 for 3-D printing, Hapkit 3.0's base has a circular shape to prevent warping during the 3-D printing process (Figure 6a). It also has a slimmer support for the paddle with no adjustment bar to save 3-D printing material and eliminate screw components.

B. First use in a haptics class: Lessons we are learning

Our first test of Hapkit 3.0 began in October 2015 in a 30-person graduate haptics class at Stanford University. Capstan drive assembly was achieved by all students in less than five minutes. During an intensive first haptic rendering assignment, we observed many unstable renderings during which no capstan drives became unwound. However, the robust transmission combined with stops at the end of the Hapkit 3.0 workspace (not present in Hapkit 2.0) caused about a third of the 3-D printed drive wheels to shear off of the motor shafts. Improvements to the drive wheel design, which had weaknesses due to the resolution of the 3-D printing process, corrected this problem. Additionally, students in the class enjoyed the handle customization, which we posit leads to increased sense of ownership and thus engagement in the course material. Testing of Hapkit 3.0 in this course and in its public release at `http://hapkit.stanford.edu` will allow us to further analyze the performance of this design.

V. CONCLUSIONS

We presented the evolution of the Hapkit to the latest 3-D printed design, based on our use of the devices in a variety of educational environments. We focused on qualitative observations that drove practical design changes for educational applications. In future work we will take advantage of the ability of Hapkit to record user's motion and forces to develop a system to collect and process students usage data as proposed in [30]. We are also performing quantitative analysis of Hapkit device dynamics and control, perception of virtual environments with Hapkit, and its impact on learning – we expect these additional studies to yield further design improvements. Another important contribution is developing a more intuitive programming language for educational haptics applications, for use by teachers and students. This work is mainly being pursued by collaborators at the University of British Columbia.

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