Spurring Innovation in Spatial Haptics

How Open-Source Hardware Can Turn Creativity Loose

By Michael Yip and Jonas Forsslund

This article discusses an open-hardware robotics kit approach for designing spatial haptic interfaces. Our development of an open-source haptic device kit called *WoodenHaptics*, for which blueprints have been made available online for free download, enables interaction designers with little electromechanical experience to modify, manufacture, and assemble fully working haptic devices. This article addresses the processes of open-sourcing spatial haptic devices by covering the key mechanical and electrical principles needed for high-fidelity haptic rendering, the mathematical foundations for spatial haptics, the challenges to open-sourcing software and hardware and teaching it to different communities, and the history of the WoodenHaptics project itself.

A particular focus here is the general steps that have been taken to ensure a haptic interface design that is easy to replicate and modify, while at the same time being cost effective without losing high-fidelity force reflection. The results from an interview study with initial external users are reported. In addition, we contribute lessons learned from the process of shifting the device out of the research lab where it was initially created and toward replication elsewhere.

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Lowering the Barriers to Inspire Experimentation

Spatial haptic interfaces are grounded human interface devices that track a physical manipulandum (handle) in space and can reflect a directional force on that manipulandum and consequently on the user. With a spatial haptic device and appropriate haptic rendering algorithms, an end user can explore a virtual environment using the sense of touch [1]. This technology, with roots in force-reflecting hand controllers developed for remote manipulation in space and made popular with the advent of the popular Phantom [2] in the early 90s, has yet to achieve a wide dissemination. One reason is the multidisciplinary and often tacit knowledge that so far has limited construction of new devices to a few highly specialized robotics labs.

This is why we developed WoodenHaptics (Figure 1), an open-source kit for a three-degrees-of-freedom (3-DoF)

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haptic device conceptually similar to the Phantom, packaged as an open-hardware and open-software starter kit for design explorations. First introduced in 2015 [3], WoodenHaptics promotes the philosophy of what is called *sketching in hardware* [4], where subsystems are carefully formed that encapsulate certain technical details (e.g., the electrical system), whereas others are highly visible (the mechanical structure and wire rope power transmission). This is intended to help designers quickly explore physical variations of a design in a hands-on fashion, thus focusing on designing for their application rather than problem solving an array of mechanical and electrical details. Since the kit itself is open source, it opens up for deeper modification, including its electronics box, for those designers who are so interested, though such alteration is not necessary for most applications.

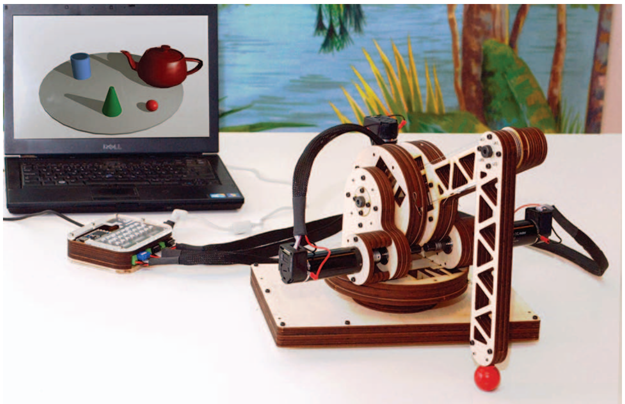

Figure 1. The fully assembled WoodenHaptics device, with motor drivers and USB interface. The motion of the ball grip corresponds to that of the rendered ball on the screen, and virtual collision forces are reflected onto the ball grip.

Background

With the advent of Massie's force-reflecting device in 1993 [2], spatial haptics as a multipurpose human–computer interaction (HCI) interface became popular through the commercialized Phantom series and other devices available on the market today. While all these devices can read a spatial position and render a directional force back to the user through the manipulandum, the experience and quality of the forces and movement are quite different, something that is reflected in the price tag, which ranges from US$300 to over US$20,000.

Since only a limited design space is covered in terms of fidelity, price, and capabilities (e.g., workspace dimensions and maximum force) by commercially available devices, application-specific devices have sometimes been developed, such as for simulation of microsurgical bone drilling [5]. However, engineering a haptic device is a large commitment and feasible only in highly specialized robotics labs that have the mathematical and mechanical know-how to realize and achieve high-quality haptics in their design. Without adaptation of the device hardware, there is a fundamental limitation on the quality of the haptic rendering for a particular application [6]. Thus, for more widespread adoption and innovation of spatial haptic devices, algorithms, and applications, this inaccessibility of haptic device design and physical implementation needs to be overcome. In other words, a more accessible means of implementing application-specific spatial haptics hardware is required.

A great deal of fundamental theory for building a haptic device has been described in, for example, [7] and [8]. However, bridging the gap from reading the fundamentals to constructing a fully functional three-dimensional (3-D) spatial haptic device is still a daunting task for a common interaction designer and is feasible only for an expert roboticist. Significant practical and tacit knowledge is required to actually put together a high-fidelity haptic device, since it involves making a correct combination of design choices, ranging from the selection motors and motor drivers (type, size, and electronics), the form of the mechanical structure, the underlying control paradigm, and even the type of fasteners (e.g., screws) to choose for assembly. Then the parts need to be located and purchased, which can be very time consuming and confusing. Furthermore, the robotics literature describing the mathematics required to operate the haptic device [7] may be overwhelming in scope and content to the electromechanical novice.

One promising approach to lowering the barrier for engineering haptic devices is developing kits or tools specifically designed for the task. The development of kits and tools for design through making is an active research area in itself [9]–[12]. A successful translation of this effort is Phidgets [9], used to simplify development of physical interfaces through providing everyday programmers with a kit of premade electronic physical widgets. Toolkits such as Phidgets have been described as being particularly instrumental for sketching in hardware. Software tools have been developed explicitly targeting designers who have no production training, such as in electronics breadboarding [10]. Even the notion of a so-called untoolkit has been proposed: a conceptual tool to leverage existing standard materials and components to create new artifacts [11]. This provides users with novel and more accessible tools that simplify the use of widespread professional components rather than a limited set of unique parts in a box. Open-source hardware, when designed correctly, also allows designers to focus on only those aspects of the product pertinent to the designers' interest, trusting that the rest of the system can adapt, which has been shown by Mellis and Buechley [13] to be valuable in workshops. In the haptics domain, the other notable haptic tool kit currently maintained is the Hapkit [14], a 1-axis paddle for force feedback that is constructed with the goal of teaching engineering concepts through hands-on experience.

This article extends previous work on WoodenHaptics [3], where WoodenHaptics was introduced as a starter kit for materials exploration, design, and realization of application-specific force-reflecting haptic devices, primarily for the HCI community. In this article, we elaborate our efforts to make the kit itself open source, and we report on the early community reception.

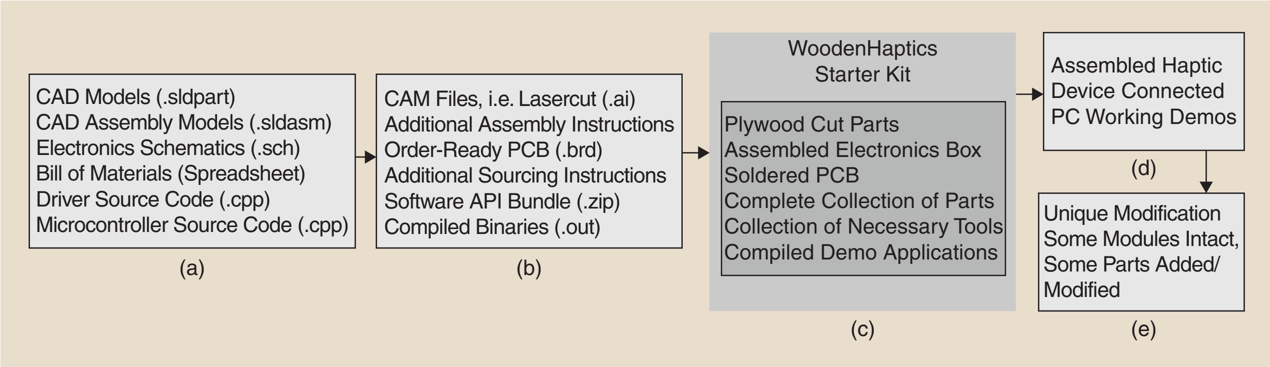

Figure 2. The different levels at which WoodenHaptics can be approached. Digital files can be hosted on a public version control system (such as GitHub). (a) The source is the digital files mentioned in the box. Also, (b) for convenience, fabrication-ready files are provided, with the additional benefit, in case of laser-cut vector graphics files, of being more accessible to non-CAD users. Most users or facilitators, however, are presumed to approach a (c) prepackaged physical kit, which the user or facilitator may fabricate. (d) Assembling the contents of the starter kit results in a fully working device and gives construction experience useful prior to (e) deciding to start on a new device or explore variations. CAM: computer-assisted manufacturing.

Figure 3. The parts included in the kit. Not shown here are the three motors, the electrical cables and electronics box (Figure 4), and the configurable software that complete the kit.

What distinguishes our kit from a tool kit is that we provide one reference design rather than a set of generic components. The term *starter kit* is derived from the concept of hobbyist starter kits—for example, in model train sets. A working device can be built but can also be extended or changed. The kit can be approached both in its digital source form and as a physical kit (Figure 2). The intended audience is nonexperts interested in haptic device exploration, especially for applications requiring different form factors (e.g., length of arms) and other properties (e.g., maximum force) that off-the-shelf devices won't provide—something we in our own practice have seen a need for.

Kit Contents, Fabrication, and Use

The kit, once fabricated from its digital plans, consists of a complete set of hardware components that make up a full spatial haptic device. This includes all the precut plywood parts, screws, bearings, and other mechanical components (Figure 3). The kit is completed with three motors (Maxon RE40) with premounted encoders and an electronics box (Figure 4) that connects to a 48-V laboratory power supply and a stationary personal computer (PC) equipped with a data acquisition interface (DAQ). The DAQ used is the Sensoray S826, a PCI express slot card. Alternatively, at the cost of lower maximum update rates, the mbed microcontroller platform can be used, which enables a generic universal serial bus (USB) interface (Figure 4). The kit requires only a limited set of tools: hex keys, a steel-wire crimping tool and cutters, a butane torch, and an arbor press (Figure 5). A list of these tools and where to purchase them is available online, and several tools (such as the torch and press) are low cost (approximately US$11.20) but can also be replaced by such items as a lighter and a mallet. The approximate parts cost of the kit is between approximately US$2,670 and approximately US$3,740, depending on whether the DAQ or USB/mbed is used, if wooden parts are cut locally or ordered, and if any tools need to be purchased. The single largest cost is the motors: approximately US$1,520 for three RE40s with encoders. The software required to operate the device is included as well, in the form of an extension to the open-source haptics application programming interface (API) Chai3D 3.0. Thus, the builder can immediately run available demo programs and proceed to application-specific development.

The nonstandard parts and components are designed to be fabricated using digital (and personal) fabrication processes by the user or by a company on behalf of the user. The kit is thus digital in the form of order-ready laser-cut flat-sheet vector drawings, printed circuit board (PCB) layouts, and a spreadsheet of parts and suppliers. The underlying design files, that is, computer-assisted design (CAD) models and circuit schemes, are available as well for those interested in modifying a specific module.

Assembly

All the structural pieces are manufactured from 6-mm plywood sheets using a laser cutter. To form stiff 3-D parts from

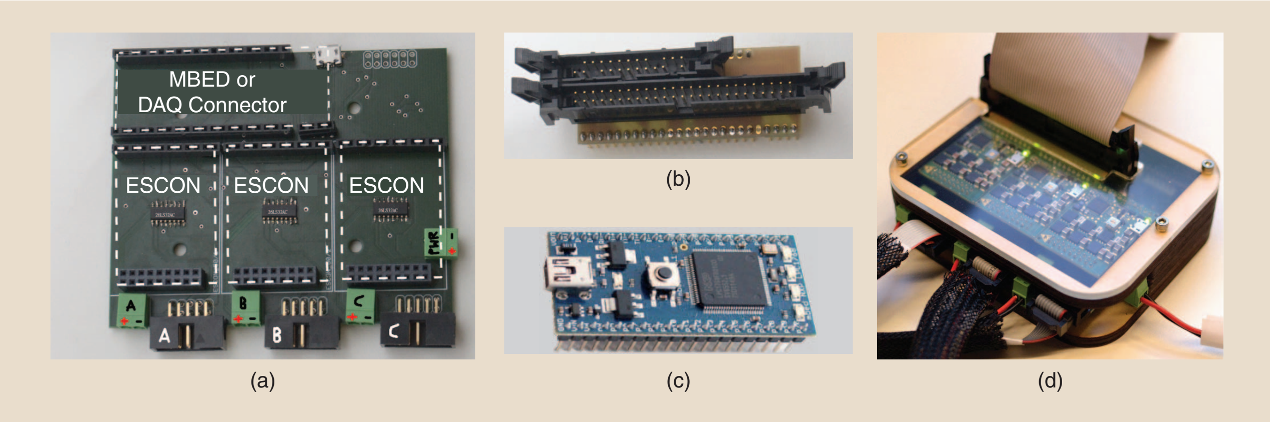

Figure 4. The PCB-based electronics box used as an intermittent between the motors/encoders and the PC. (a) The custom-made motherboard houses three ESCON current driver modules and can be equipped with an attachment for (b) a DAQ connection or (c) an mbed-compatible microcontroller platform, in which case the motherboard USB port is used to interface with the PC. (d) The default configuration is to use the DAQ connector.

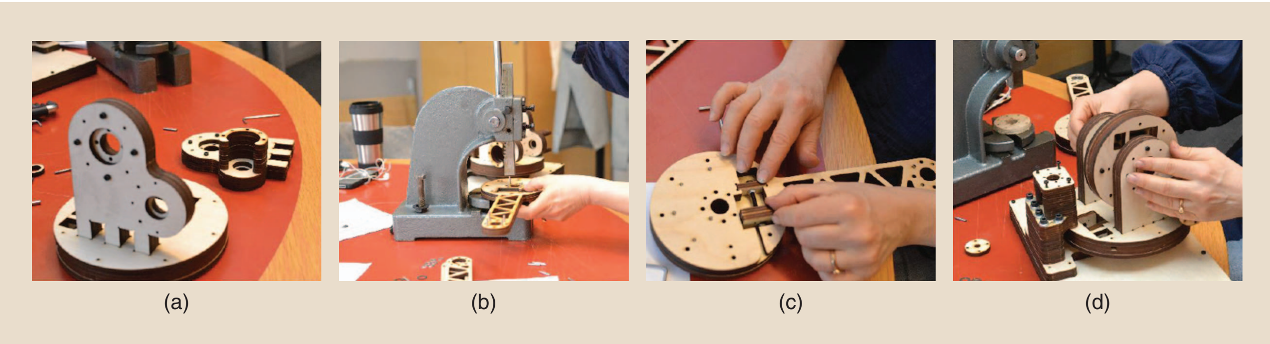

Figure 5. User assembly of the wooden haptics device. The 3-D structure is formed from plywood sheets by (a) press-fit finger joints, (b) stacking and aligning sheets with dowel pins, (c) creating a tensioning mechanism, and (d) mounting the subassemblies (bodies) with high-quality rods and bearings.

the flat sheets, several layers are stacked and held together with screws. All holes in the plywood parts are located with submillimeter precision, such that all screws can self-tap (self-thread) the holes, allowing for quick assembly and disassembly. Stacked parts are aligned by inserting dowel pins (precision cylindrical pins) with an arbor press before adding screws. Bearings are press-fit as well using the arbor press. In fact, there is no use of bondants or adhesives, resulting in a visually and mechanically clean, quickly disassemblable, and reconfigurable device. The kit comes with instructions and video documentation on how to assemble the main bodies.

The bodies A, B, and C (Figure 6) form the three links or DoF that together enable the tip of the device (P in Figure 7) to be moved left and right, up and down, and in and out. Each DoF is coupled independently to a motor through wire rope. The angle of each DoF is a fixed ratio to the rotation of the motor shaft, and therefore the angles are measured by the encoders mounted on each motor (Figure 8).

Wire Rope Cabling

The device utilizes cable drive for all its transmissions. A strong steel wire rope transmits the power from each motor to its own respective link. Figure 8 shows a standard cable drive

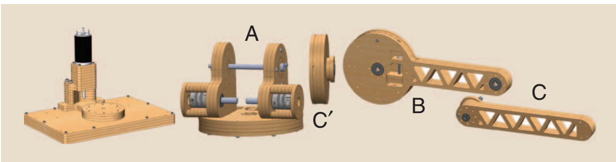

Figure 6. The user-assembled bodies: The base drives body A, which in turn drives body B and, indirectly through C′, body C.

transmission used in all DoF. The motor shaft is attached to the capstan, which is a shaft for a cable to wrap around and grip. The cable makes five wraps around the capstan and is terminated at both ends. The cable needs to be taut to grip the capstan, which is done at the termination by either tightening or loosening a screw. For the last link, a loop of cable is used as a timing belt to connect pulley C′ to body C, and a turnbuckle is used to adjust the loop tightness. Now, for each body, when the capstan is rotated with the cable gripped firmly to it, the body is then rotated; alternately, when the body is rotated, the capstan is subsequently rotated. This completes the transmission assembly, allowing for the motors and the driven axis to not require collocation. This allows for gearing up of the motor torques to achieve larger forces without using gearboxes and for easy replacement of motors. The reasons

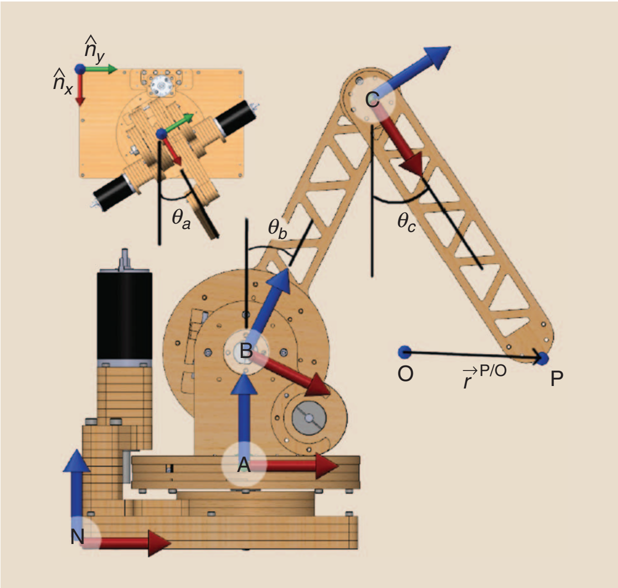

Figure 7. The device is a serially linked mechanism, whose base is fixed in a reference frame $N = \hat{n}_x, \hat{n}_y, \hat{n}_z$. The position communicated from the device is defined as the vector $\vec{r}$ from the point O fixed in N to the point P, located at the end of body C. The vector can be found through forward kinematics using the angles θ_a, θ_b, and θ_c.

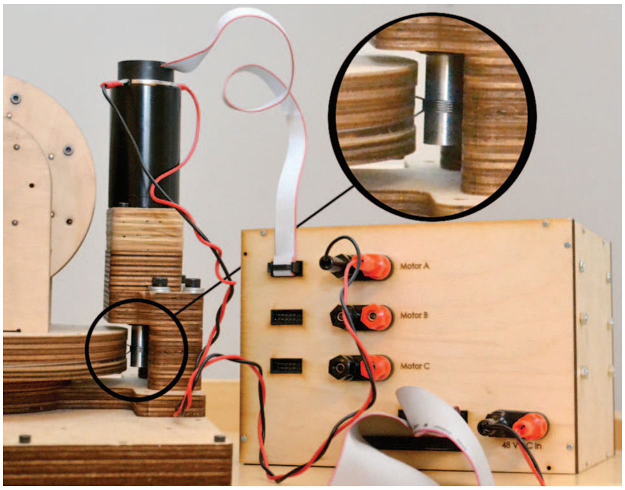

Figure 8. The first DoF motor connected with power and encoder wires to the electrical interface (of the early non-PCB-based version). The inset shows the aluminum capstan and wire rope coupling.

for these design choices are discussed in the "Fundamentals and Theory" section.

Electrical System

The kit specifies three high-quality motors, each driving a respective DoF. The designer has only to connect the encoders to the electronics box (which routes them to the computer) and each motor power cable to the respective output of the electronics box (Figures 4 and 8). Two ribbon cables connect the electronics box with the Sensoray S826 board on the PC.

Using a custom PCB (Figure 4), even when it is only handling routing of wires, has the benefits of ease of replication, avoiding loose cables, and making the device much more portable. Keeping the schematics in an actual PCB plan is also more aligned with the philosophy of digital fabrication.

The electronics box is designed such that the user can choose between working with the flexible but more expensive DAQ or attaching an easy-to-use microcontroller (mbed LPC1768, 96-MHz 32-bit ARM Cortex-M3) that connects to the computer over USB. Having the option can benefit different communities. Application designers may prefer the plug-and-play readiness and lower price of USB (currently in beta), whereas robotics researchers may desire DAQs for low-level signal processing and controls.

The motors chosen are more powerful than is common in most commercial devices. The selected motors are specified for safely allowing a maximum continuous current of 3.16 A, and we have limited the maximum current to 3 A. This means that the user will not have to worry about electrical heat, burning, and so forth, which is the case when the motors are overdriven in more than short periods of time, which is common practice otherwise.

Software Configuration

The kit is completed with a working open-source software module for the mechanical design that is part of the kit. If a dimension is changed or a tuning of the experience is desired, the user can easily modify a variable in a JSON-formatted text file to represent this change (Table 1). If the physical dimensions of the structure have been altered, then the variables of interest to change are the diameter of each capstan and body and the length of each link, as well as the mass and mass center of each body. This effectively is equivalent to changing the gearing of the motor and changing the size of the workspace, respectively. The design also affords the easy replacement of motors with different motors, but users will then need to adjust the torque/current ratio as specified in their motor data sheet. The maximum stable stiffness and damping of the complete device can be found retroactively by experimenting and adjusting the values accordingly. The device works like any other haptic device in the open-source Chai3D API [15] and is easily ported to other APIs.

Fundamentals and Theory

In this section, we will describe the following: 1) the fundamental electromechanical design principles for crafting high-quality spatial haptic devices and 2) the mathematical foundations for modeling the haptic device and producing forces from motor torques.

Fundamental Design Principles for High-Quality Haptics

High-quality haptic fidelity in spatial haptic devices aims to achieve transparency. Qualitatively speaking, a transparent haptic feedback system is one where the system and the device itself are haptically imperceptible (also known as transparent) to the user. Formally, a transparent system is one where the transfer function between the desired input and the system output

Table 1. The modifiable JSON script describing the device attributes.

```
{                                           Unit
  “diameter_capstan_a”:         0.01,    m
  “diameter_capstan_b”:         0.01,    m
  “diameter_capstan_a”:         0.01,    m
  “length_body_a”:              0.08,    m
  “length_body_b”:              0.205,   m
  “length_body_C”:              0.20,    m
  “diameter_body_a”:            0.16,    m
  “diameter_body_b”:            0.12,    m
  “diameter_body_c”:            0.12,    m
  “workspace_origin_x”:         0.22,    m
  “workspace_origin_y”:         0,       m
  “workspace_origin_z”:         0.08,    m
  “workspace_radius”:           0.1,     m
  “torque_constant_motor_a”:    0.0603,  Nm/A (see motor data sheet)
  “torque_constant_motor_b”:    0.0603,  Nm/A
  “torque_constant_motor_c”:    0.0603,  Nm/A
  “current_for_10_v_signal”:    3,       A
  “cpr_encoder_a”:              2000,    Quadrupled counts per revolution
  “cpr_encoder_b”:              2000,    Quadrupled counts per revolution
  “cpr_encoder_c”:              2000,    Quadrupled counts per revolution
  “max_linear_force”:           12,      N
  “max_linear_stiffness”:       5000,    N/m
  “max_linear_damping”:         8,       N/(m/s)
  “mass_body_b”:                0.17,    kg
  “mass_body_c”:                0.11,    kg
  “length_cm_body_b”:           0.051,   m to center of mass from body a
  “length_cm_body_c”:           0.091,   m to center of mass from body b
  “g_constant”:                 9.81     m/s^2;0=no gravity compensation
}
```

variables (usually forces and velocities) consists of only a gain term. If the gain is 1, then the forces and velocities are exactly replicated. The transparency of a system is dependent on both the mechanical fabrication and transmission system of the haptic device as well as the electronics and communication protocols between the device and the PC.

The WoodenHaptics reference design maximizes the haptic transparency of the system by minimizing the following nonidealities: friction (resulting in diminished haptic perception), backlash (resulting in chatter in the motors and the device), structural compliance (resulting in a loss of ability to perceive stiff environments), and device inertia. This was done by using cable drive for motor transmissions, pulley-based gearing as opposed to teeth gearing, aligned and stacked materials, and cored frames, respectively.

Each joint is operated through a motor, encoder, and capstan. The motor-to-capstan combination is connected through a flexible shaft coupler, which acts not only to reduce friction caused by misalignments in the axes of the motor and the capstan but also serves as an easy way to swap out different motors and find the best motor for an application without performing any disassembly of the cable transmission. Each motor is mounted in such a way that its motions are decoupled from those of all other motors. This is achieved by mounting the second- and third-axis motors on the rotating base (body A, Figure 7). This choice highlights the following design considerations: the simplified and shorter cable routing minimizes moving components and therefore reduces friction; the placement of the motors and motor couplings allows for easy access to, removal of, and installation of other motors of different sizes; and shorter cable routing reduces the chance of the transmission decabling. Independent axis control also means that failure in the cable transmission (e.g., the cable snapping or coming loose) in one axis does not affect (decable or loosen) any other axis.

Although motor and gearbox combinations are commercially much more common, cable drive transmission is the standard for haptic devices, because it provides a near-frictionless transmission and has no backlash, which nearly no gearbox can achieve. (We note that harmonic drives are a unique zero-backlash gearbox but still dissipate energy via the wave gear from friction loss.) A high-tensile-strength cable is necessary to maintain the stiffness of the transmission and reflect high stiffnesses. At the same time, an ultraflexible cable is advantageous, as it reduces the forces required to bend and unbend the cable as the capstan rolls. Uncoated stainless steel cables with a high count of individual steel fibers are used (we use a 0.54-mm-diameter, 16-kg-rated stainless steel rope with fibers in a 7×7 configuration).

As the cable wraps around, the grip of the cable on the capstan increases exponentially (according to $F_{\text{grip}} = e^{\mu\theta}$, where μ is the coefficient of friction between the steel cable and the aluminum capstan), and therefore even a few turns will immediately prevent the cable from slipping. We note that dissimilar metals provide a higher coefficient of friction, so we attain high grip forces with aluminum and steel. In practice, five turns is more than enough to prevent any slipping between the capstan and the cable. This principle is also how the final link's cable transmission (using the cable loop and turnbuckle) works without slipping.

Regarding device compliance, increasing stiffness (i.e., reducing compliance) in the device's structure is done by increasing the second moment of inertia of each link (e.g., making links wider so they do not twist), improving joint stiffness (e.g., by increasing shaft diameters and increasing the distance between the shaft bearings that hold the shafts straight), and using a stiff material. Because plywood is a layered composite, it is in fact quite stiff, is unlikely to split, and yet is still reasonably light. It is also soft enough for self-tapping holes and very minor misalignments that all contribute to making the device more accessible and forgiving to build, without sacrificing substantial haptic fidelity.

Electrical System

The electrical system has two purposes: to drive the motors and to measure their angular position. The torque of the motor used is proportional to the current that is driven through it, not the voltage it is supplied. Therefore, a current or torque controller (in our case Maxon ESCON 50/5) is connected between a generic power supply and the motor.

It is worth mentioning that the components used (motors, amplifiers, encoders, and acquisition card) are of professional laboratory quality and should not be confused with hobbyist counterparts. While efforts to replace them with lower-cost alternatives are most welcome, one has to be careful to preserve the precision needed. For example, the delay has to be less than 1 ms, and the resolution and quality of the digital/analog converter sufficient. However, this also brings to the surface the potentials of this starter kit, as it allows users to explore what their haptic tolerance is for lower-cost alternatives.

Mathematical Description and Analysis

The haptic device is displayed in a virtual environment as a point (avatar) in the virtual environment; its location is determined via a forward kinematics representation. The forward kinematics is defined as $f(\boldsymbol{\Theta})$, where $\boldsymbol{\Theta} = \{\theta_a, \theta_b, \theta_c\}$ is a vector of the joint angles. In this case, the manipulandum is in the form of a classic RRR configuration manipulator: three moving links that are serially linked through revolute (R) joints (Figure 7). However, the motor for the end link is driven from the rotating base A, with the angle θ_c being defined with respect to the spinning axis $\hat{a}_z = \hat{n}_z$ at A. This in fact makes the equations of motion simpler, as can be seen in the following forward kinematics model for the device:

$$ {}^{N}\vec{r}_P = f(\theta) = \begin{bmatrix} \cos\theta_a (L_b \sin\theta_b + L_c \sin\theta_c) \\ \sin\theta_a (L_b \sin\theta_b + L_c \sin\theta_c) \\ L_b \cos\theta_b - L_c \cos\theta_c \end{bmatrix}, \tag{1} $$

where L is the length of each body's center of rotation to the next. The partial derivatives of the forward kinematics gives the device's Jacobian matrix $\mathbf{J}$:

$$ \mathbf{J} = \left[\frac{\partial f}{\partial \theta_a} \frac{\partial f}{\partial \theta_b} \frac{\partial f}{\partial \theta_c} \right] \tag{2} $$

$$ = \begin{bmatrix} -\sin\theta_a (L_b \sin\theta_b + L_c \sin\theta_c) & L_b \cos\theta_a \cos\theta_b & L_c \cos\theta_a \cos\theta_c) \\ \cos\theta_a (L_b \sin\theta_b + L_c \sin\theta_c) & L_b \sin\theta_a \cos\theta_b & L_c \sin\theta_a \cos\theta_c) \\ 0 & -L_b \sin\theta_b & L_c \sin\theta_c \end{bmatrix}, \tag{3} $$

where $\mathbf{v} = \mathbf{J}\dot{\theta}$ and $\mathbf{v}$ is the velocity of $\mathbf{P}$. To give a force $\mathbf{F}$ at the manipulandum, the body torque τ is computed as

$$ \tau = \mathbf{J}^{\top}\mathbf{F}. \tag{4} $$

To see this derivation, we consider the ideal case where the power delivered by the motors is transferred completely to the end effector (conservation of energy). Let $\dot{\boldsymbol{\Theta}}$ be the rotational velocities of the system; then

$$ \begin{aligned} \dot{\theta}^{\top}\tau &= \mathbf{v}^{\top}\mathbf{F} \\ \dot{\theta}^{\top}\tau &= (\mathbf{J}\dot{\theta})^{\top}\mathbf{F} \\ \dot{\theta}^{\top} &= \dot{\theta}^{\top}\mathbf{J}^{\top}\mathbf{F} \\ \tau &= \mathbf{J}^{\top}\mathbf{F}. \end{aligned} \tag{5} $$

It can be seen here how nonidealities in the system and transmission can degrade the assumption of mechanical energy conservation (some of it being lost to heat from friction and into spring energy from compliance) and why these factors are important to minimize when aiming for high haptic transparency.

A final necessity to account for is the weight of the manipulandum. Without compensating for the manipulandum weight, users will have to hold up the device's weight in their hands. To compensate for gravity, the mass of the last two links and their centers of gravity are estimated, and motor torques to counter gravity forces are applied. Let us assume the mass of link B and link C, m_B and m_C, are located at distances l_b, l_c from axis B and C, respectively. Then, the additive torques to compensate for gravity $\boldsymbol{\tau}_g$ are

$$\boldsymbol{\tau}_g = g\begin{bmatrix} 0 \\ m_B l_b \sin\theta_b + m_C(l_b + l_c)\sin\theta_c \\ m_C l_c \sin\theta_c \end{bmatrix} \quad (6)$$

so that the torque at each joint to be commanded is $\tau' = \tau + \tau_g$. To translate the torque at each joint to the torques at the motor, we can identify the gearing ratios in a gain matrix $\mathbf{K} = diag(k_1, k_2, k_3)$, with gearing ratios for each motor axis from the pulley diameters $k_i = d_{\text{pulley},i}/d_{\text{capstan},i}$, $i = 1..3$. The motor torques are then $\tau_m = \mathbf{K}\tau'$. Finally, when using dc motors, the torque constant K_c converts the desired current to the resultant torque, and thus the current i to drive each motor is $\mathbf{i} = \mathbf{K_c}^{-1}\tau_m$.

Variations That Affect Haptic Feedback

While WoodenHaptics provides everything needed to complete a functioning device, the intention is to invite the designer to create modifications and variants of the design. Following, we highlight a few interesting areas worthy of exploration.

Workspace

Users can very easily try different sizes (lengths) of the body, and experience the difference in scaling up or scaling down their reachable workspace and the haptic perception. Figure 9 depicts a version with shorter arms that also, as a direct consequence, can render larger forces (Table 2).

Motors and Encoders

The user can switch between using high-cost, high-quality motors and encoders to using low-cost alternatives. This allows the designer to identify the specific factors and limits of haptic fidelity (e.g., the backlash from a geared motor versus ungeared motor, the cogging or friction from a US$20 hobby shop motor versus a US$300 motor). The effects of motor size can also be investigated. Figure 10 shows some motors of interest.

Cogging torque is present in all dc motors that have an iron core to assist with windings. This causes perceptible ticks when the motor is turning that can degrade haptic feedback and is a disturbance in the force output. We choose to supply more expensive, coreless motors with armature cage windings (Maxon Motors and Faulhaber are examples of suppliers with sourceable, coreless dc motors) so there is no cogging torque and so the manipulandum feels smooth to operate. For low-cost devices such as the Novint Falcon, anticogging software is used, where motors are calibrated and cogging torques are subtracted by an additional current feed-forward term. This results in a humming sensation through the manipulandum, yet it also reduces the perceived cogging torques [16].

Material

Plastics such as acrylic are as easy to cut as plywood and come in different colors for the designer to experiment with, but they can be brittle. They also tend to be heavier and have to be supported with more motor torque for gravity compensation. Increased stiffness can be achieved by using other materials, such as aluminum (which can be cut into sheets using a waterjet rather than a laser cutter). This metal

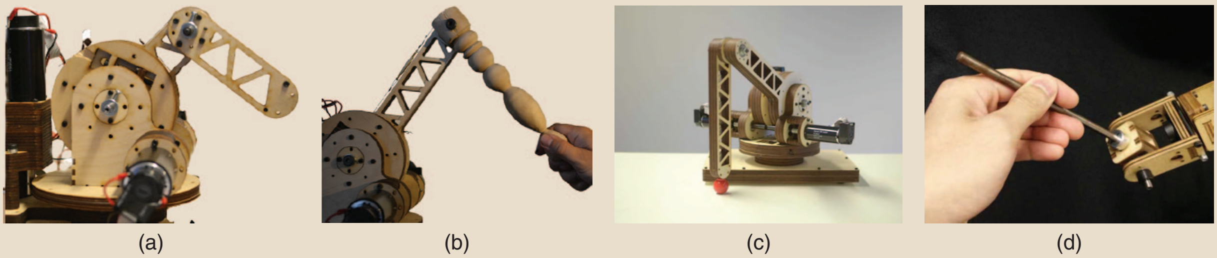

Figure 9. Exploring design variants. (a) A MiniWoodenHaptics with a smaller workspace and larger forces and (b) a different handle arm, crafted using a lathe. Adding (c) a ball-grip handle provides instant improvements to comfort, while (d) a stylus has been designed for applications where a pen interface is more natural. Ultimately, these modifications are up to the experimenter to use or build upon.

Table 2. Comparing the WoodenHaptics starter kit to commercial devices.

	WoodenHaptics	MiniWoodenHaptics	Omni	Falcon
Workspace* (mm)	200	80	100	60
Peak force (N)	9.9	19.0	3.3	8.9
Continuous force (N)	9.9	19.0	0.88	8.9
Friction** (N)	0.6/0.7/0.9	0.6/1.0/0.9	0.2/0.4/1.1	1.2/3.6/1.3

*Workspace is described as the diameter of the largest sphere that fits.
**Measured side-to-side, in-and-out, and up-and-down backdrive forces.

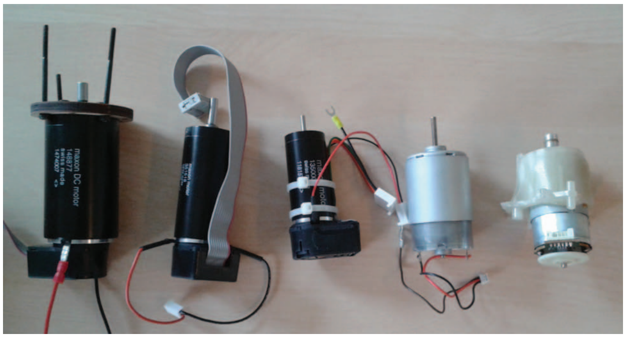

Figure 10. Some different motors that have been used for haptic devices: (from left) Maxon RE40, Maxon RE30, Maxon RE25 (Phantom), Mabuchi RS-555PH (Falcon), Mabuchi RS-455PA (Omni).

can result in a stiffer and in fact lighter device. (The density of 6061 aluminum is 2,700 kg/m^3 as compared to Baltic birch plywood at approximately 3,500 kg/m^3.) Its strength also allows increasing porosity in the structures without losing structural integrity. The disadvantage is the higher material cost, requiring all screw holes to be tapped separately, and tighter tolerances for the press-fits of bearings and finger joints. Choices of solid and composite woods can provide different stiffness and weight tradeoffs. Physical stiffness, the inertia of the device, and even visual appeal can be explored by using different materials. Figure 9 shows a variant where one part is hand-fabricated from solid wood using a lathe.

Add-Ons

A user may add buttons, sensors, or even vibrotactile actuators on the manipulandum, which can further improve the perception of textures [17]. Different grips or end attachments that interface with the user can be explored.

Community Reception

Our previous studies [3] showed that the user experience of the final device, in terms of perceived stiffness and related characteristics, was rated as most similar to that of the Phantom Desktop, the most expensive device in the test. It was also shown how it was possible for a nonengineer to assemble the device, under supervision, using a limited set of tools in an ordinary office environment [3]. The assembly (Figure 5) took 11 h stretched over a few sessions. The kit was provided to users in its physical form and facilitated by one of the authors.

In this section, we present a case study of the early community reception. Since WoodenHaptics' initial public release in January 2015, about 30 people have made online inquiries about purchasing the kit, and one external group has successfully built the device themselves. Except for that group, too few have yet constructed the device to validate its community impact as a whole or whether the kit works for a particular user goal for users in general. Nevertheless, we can learn more about how current and potential users appropriate the kit, what value they think it brings, and what limitations they see through an in-depth case study. Borrowing from the wide use of such studies in HCI, a case study is defined as "an in-depth study of a specific instance (or a small number of instances) within a specific real-life context" [18] and is used for several reasons, including 1) exploration, that is, to understand novel problems or situations, 2) description, that is, documenting a context of technology use, or 3) demonstration, namely, showing how a new tool was successfully used.

Our study is demonstrating one case where the kit was successfully used by a large company to create a public demo. The study also shines a light on various perspectives of open-source robotics use, for example, for supporting learning goals in education, including for both teachers and learners in engineering as well as for technological novices.

Practically, the study comprises in-depth semistructured interviews with seven subjects (male, aged 23–48, the average being 32, representing four different nationalities). Two interviews were done in person and three by video link, of which one was a group interview with three subjects. All participants consented to their involvement and to being recording for confidential analysis by the researchers. A semistructured interview protocol was used, and each interview lasted 30–60 min. Notes taken during the interviews were partly transcribed and analyzed and sorted into themes.

Two of the respondents, both professional engineers but with different backgrounds, had built the device, one using plywood and the other acrylic. A third was a professor who had shown interest in using the device primarily for teaching mechatronics and controls. A fourth was a master's student in HCI with a nonengineering background, and the last three were mechatronics engineering students. Apart from the professor, none of the respondents had prior formal haptics or robotics training, but all had some experience building physical things.

Results

The results of the interviews can be sorted in terms of 1) motivation, including the motivation of those who built the device and of those who expressed an interest in doing so, 2) the building experience regarding sourcing components, 3) manufacturing, and 4) assembly.

Motivation

While the number of respondents in this study was small, they represented a wide spectrum of motivation for building their own WoodenHaptics device. The two who had already built one wanted to produce a public technical demo displaying their corporation's technology along with haptic remote control. They mentioned as important factors having control over all aspects of the technology as well as the ability to render high stiffness and forces. The HCI student became interested in haptics after a visit to a surgery simulation facility and wanted to explore it further without a particular application in mind and was intrigued by its particular aesthetics. This person commented: "I really like the look and feel of the product. It's got this craft feel to it. It's not like a final product—you know, totally refined and built in a factory somewhere. To keep that spirit, I should actually build it myself rather than getting everything assembled by someone else. And you could learn how it is actually built, how it works, the mechanism behind it. I'm curious about it."

The professor thought the device would suit his institution's educational style and suggested that depending on the course one could exclude or include various moments of the building experience. For example, an electronics class could design and make their own H-bridge but have the rest provided, or vice versa.

Sourcing of Components and Parts

The two in the study from the corporation sourced components themselves using the suggested suppliers, except for the variant in acrylic, which was sourced from a local laser-cutting supplier. They had no preference on sourcing parts from one or several suppliers. The same was true for the mechatronics students, for whom the sourcing was part of the learning experience. However, for the self-directed HCI student, who was also currently living abroad, the sourcing of parts from various vendors was a big obstacle, and he would have preferred receiving everything as a physical kit. The professor expressed appreciation for the possibility to source and manufacture independently using the open-source drawings as well as to buy premade modules, kits, or complete devices.

The sourcing of parts was successful, but not without some unexpected obstacles. The laser-cut parts aside, some issues included suppliers sending the wrong cable, some components damaged and in need of replacement, a few parts missing from the bill of materials, and a DAQ card with a nondefault jumper configuration. Receiving all parts unsorted was reported to be a bit overwhelming at first.

Manufacturing: Laser Cutting and Making the PCB

The respondents, who lacked access to their own laser-cutting machine, used an online service for getting the laser-cut plywood parts, including the material, and used a local company for the acrylic. They reported several issues before achieving success:

- The plywood varied in thickness from one order to the next, and since they were stacked even small deviations accumulated. Consequently, some screws became too short.
- The holes were sometimes skewed cut, which mismatched stacked holes, making it impossible to insert dowel pins.
- Conversion of file formats one time resulted in millimeters being interpreted as inches, resulting in comically large parts.
- Some iterations on adjusting dimensions were made, especially for the acrylic version.

While the laser-cutting service provider did not work with tolerances, asking for sheets of 6.0-mm or fewer thickness and as straight-cut as possible eventually proved successful. Also, the fact that changes were possible to make directly in the vector drawings without using CAD was appreciated. PCBs were easy to order, but the respondent accidentally soldered a component in the wrong direction. He found it useful to have ordered spare parts and PCBs for such mistakes.

Assembly Experience

The first respondent assembled the device independently, except for the device cabling, which he found the most challenging, for which he sought the assistance of someone more experienced. Since he eventually built several devices, he accumulated tacit knowledge of the assembly process, using tricks with such things as tape, tension, and cutting in the right order, and could pass on this knowledge when supervising the next builder. He found CAD software (SolidWorks) useful for visualizing the assembly but noted that the CAD software's interface could be confusing to newcomers. The respondent building the acrylic version had access to the previously built wooden version, which proved helpful. Acrylic was reported to be more difficult to assemble due to its brittleness.

Something the respondents would have preferred was to have the components, both laser-cut and metal parts, sorted into bags according to which body they belonged to. While the laser-cut parts were originally placed on different sheets according to their respective body, minimizing material waste by combining all the parts on a small number of sheets was done in the cutting process. The comment suggests that a facilitator, if the kit is purchased, could help by sorting parts or that the user could be instructed to do so at the start of the assembly.

Discussion

We have shown how the WoodenHaptics starter kit can be an engaging spatial haptics device test bed without many of the issues usually involved in the craft. It serves to

- help users understanding the fundamentals of the mechanism; for example, it shows clearly how three motors combine to generate a force vector at the end of the manipulandum
- enable users to incorporate the device easily into their projects without having to be an electromechanical expert
- enable exploration of the user experience (changing or tuning certain parameters or replacing components)
- establish a common language between designers and experienced hardware engineers.

With WoodenHaptics, a designer can create variations of a serially linked 3-DoF grounded spatial haptic device. The constraints imposed by the kit frees the designer from having to solve many electrical, computational, and mechanical problems, since these have already been solved, and reduces the overall barrier to exploring spatial haptics [19] It instead allows the user to innovate in terms of motor choices, workspace dimensions, physical materials, aesthetics, and extended functions such as buttons. As personal fabrication of parts becomes easier—for example, through direct interaction with a laser cutter or software tools—designers can quickly explore different variations that can optimize their haptic experience

Table 3. The sourcing of the components.

Category	Item	Description	Suppliers	Approximate Cost**
		Mechanical Components		
Structure	Plywood	6.0-mm-thick Baltic birch five-ply (four 600 × 600-mm sheets)	Cutlasercut.com (U.K.), local lumberyard*	US$190 (with cutting), US$40 (material)
Fastening	Screws, dowel pins, shoulder bolts, nuts, washers	Fastening for assembly	Misumi (international), McMaster-Carr (USA)*, local hardware store*	US$45
Transmission, excluding cable	Shafts, flexible shaft couplers, ball bearings, spring washers, wire rope	Mechanical components for transmission and assembly	Misumi (international), McMaster-Carr (USA)*, VXB (international)*, SDP-SI (USA)*	US$160
Cabling (wire rope)	0.54-mm flexible stainless steel wire rope, double ferrule, miniature turnbuckle	Cable for mechanical power transmission and fastening	Tecni-Cable (U.K.), Hobbykellershop (Germany)***, McMaster-Carr (USA)*	US$20 (tools + US$75)
		Electrical Components		
Motor	Coreless dc motors (Maxon RE40 default)	High-quality, zero-cogging motors	Maxon, Faulhaber*	3 × US$430
Encoder	Optical encoders	Angle sensing at each motor shaft	US Digital (USA)* or preattached to motor (Maxon, Faulhaber)*	3 × US$75
Motor driver	Current/torque control motor driver (ESCON 50/5)	Embedded solution for current control	Maxon (international), Copley (USA)*	3 × US$160
Electronics box	PCB, connectors and cables, mounting screws, differential decoder, power supply	Failsafe routing of connections without use of breakouts or breadboard	Farnell (international)	US$235**** (PCB), US$55 (parts), US$160 (power supply)
		PC Interface		
I/O interface	Sensoray S826 or National Instruments* or mbed*	Analog I/O, digital I/O to all motor drivers and for encoders	Sensoray (USA), National Instruments (international)*, Farnell*	US$855, US$535+*, US$55*

*Alternative supplier not in WoodenHaptics bill of materials. The complete list can be found on the project's website
**All prices in February 2017 US dollars
***For miniature turnbuckle *spannschloss*
****Minimal economical order, including extra PCBs

for a particular application. As an alternative, Morimoto et al. [14] use a single variation of their Hapkit to standardize the user's haptic experiences and reach a broad user population through massive open online courses (MOOCs) such as Coursera.

Common haptic devices and application programming interfaces sometimes provide wrong expectations of what experiences they actually support. For example, on the basis of experiments with a commercial haptic device where a virtual object specified to be of maximum stiffness still yielded a "mushy hard" sensation, Mousette [20] noted that "hardware hard is relative." It is likely that users would have had a different experience with a device equipped with more powerful motors. By crafting with WoodenHaptics, one can learn, experience, quantitatively define, and alter what we might call *mushiness* and other difficult-to-articulate haptic experiences.

Designing for Open Source

As reflected in the interviews, the respondents had different motivations and varying interests in the building process for pursuing a spatial haptics kit. Therefore, it is essential to enable users to modify the device at different stages. Stacking plywood sheets stands out in this regard as an attractive method, since it can easily be modified in CAD (WoodenHaptics uses Solidworks), in two-dimensional vector graphics software (modifications through free software such as Inkscape), and after fabrication, using carpentry hand tools. The ability to engrave text on parts could be used to assist in the sorting of parts to their logical subassemblies, that is, for the bodies A, B, and C of the WoodenHaptics device.

A challenge for the stacked plywood method is the variance in quality and thickness of the plywood sheets and the inconsistency in the precision of the cuts, especially if a service provider is contracted. However, the existence of laser-cutting firms that can ship internationally and repeatedly reproduce a design within tolerances can be a key to wider dissipation and sharing of different designs within the community. For WoodenHaptics, we have uploaded the exact files and manufacturing instructions used for a successful order of laser-cut plywood and PCBs. Providing a complete bill of materials, including the exact choice of default components and suppliers that ship internationally, is important for allowing the user to choose when to go for the default and when to substitute and do the necessary adjustments to retain compatibility with the rest (Table 3). The sourcing process could be further assisted through open-hardware-facilitating companies that provide complete physical kits or modules. Finally, as affordable 3-D printing technologies improve (with tens of microns precision features) and options for high-stiffness and low-mass materials such as aluminum extrusions are able to be formed in a precise manner, we foresee that the WoodenHaptics hardware could be fabricated using 3-D printing as well. The WoodenHaptics project is maintained at http://www.woodenhaptics.org.

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