Citation for the original published paper:

Forsslund, J., Sallnäs, E. (2015)
WoodenHaptics: A Starting Kit for Crafting Force-Reflecting Spatial Haptic Devices.
In: *Proceedings of the Ninth International Conference on Tangible, Embedded, and Embodied Interaction* (pp. 133-140). Stanford: ACM Digital Library

WoodenHaptics: A Starting Kit for Crafting Force-Reflecting Spatial Haptic Devices

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ABSTRACT

Spatial haptic interfaces have been around for 20 years. Yet, few affordable devices have been produced, and the design space in terms of physical workspace and haptic fidelity of devices that have been produced are limited and discrete. In this paper, an open-source, open-hardware module-based kit is presented that allows an interaction designer with little electro-mechanical experience to manufacture and assemble a fully working spatial haptic interface. It also allows for modification in shape and size as well as tuning of parameters to fit a particular task or application. Results from an evaluation showed that the haptic quality of the WoodenHaptics device was on par with a Phantom Desktop and that a novice could assemble it with guidance in a normal office space. This open source starting kit, uploaded free-to-download online, affords *sketching in hardware*; it “unsticks” the hardware from being a highly-specialized and esoteric craft to being an accessible and user-friendly technology, while maintaining the feel of high-fidelity haptics.

Author Keywords

Guides; do-it-yourself; open-source; open-hardware; spatial haptics; force-feedback; haptic device; hardware sketching; interaction design

ACM Classification Keywords

H.5.2. Information Interfaces and Presentation (e.g. HCI): User Interfaces (D.2.2, H.1.2, I.3.6) Haptic I/O

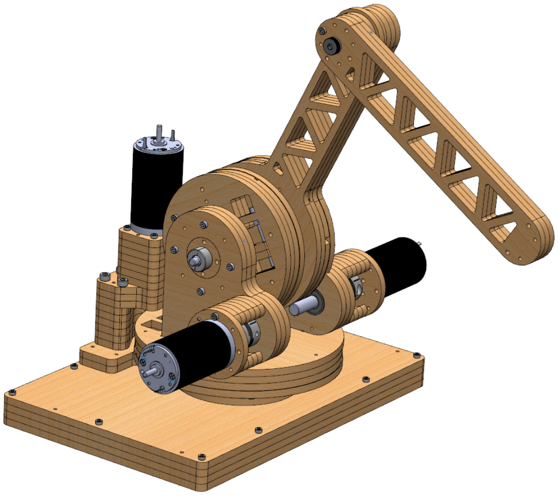

Figure 1. The completed wooden haptics device.

PART I: INTRODUCTION

Spatial haptic interfaces are grounded human interface devices that track a physical manipulandum (handle) in space, and provides the means of reflecting a directional force on that manipulandum and consequently the user. With the device and appropriate haptic rendering algorithms, an end-user can explore a virtual environment through virtual coupling between the manipulandum’s position and a representative avatar [24]. As more applications have 3D user interfaces [1], spatial haptics becomes increasingly useful for feeling the shapes of occluded objects, collisions, object stiffness and inertias, surface textures, and so on [24]. While vibrotactile haptics are ubiquitous in all cellular phones, the 3D force-displaying counterparts, spatial haptics, are not as widely present. Devices for spatial haptics have been used for surgical simulation [3], physical rehabilitation [2] and for hand tool guidance [9]. Applications in other domains could benefit from including spatial haptics, but this requires finding a good match between the qualities of the device employed and the application. The common devices commercially available (Figure 2) represent only a limited design space in terms of fidelity, price and capabilities (e.g. workspace dimensions and maximum force). Therefore, application specific devices have sometimes been developed, such as for simulation of micro-surgical bone drilling [22]. However, engineering a haptic device is still a large commitment and only feasible in highly specialized robotics labs that have the mathematical and mechanical know-how to realize and achieve high quality haptics in their design.

Research and advances in haptics tend to be focused on technological refinements and little attention is directed towards holistic design and aestetics of the devices. As a response to this, Moussette has proposed the intersection of Design and Haptics as a new field of study [17]. This approach is centered around hands-on workshops [16], exploration, making and sketching in hardware with simple haptics [18] in order to get a heightened sensitivity to haptics. The benefits that follow from this approach can be extended to spatial haptics.

TEI 2015, January 15–19, 2015, Stanford, California, USA.

ACM 978-1-4503-3305-4/15/01 ...$15.00.
http://dx.doi.org/10.1145/2677199.2680595

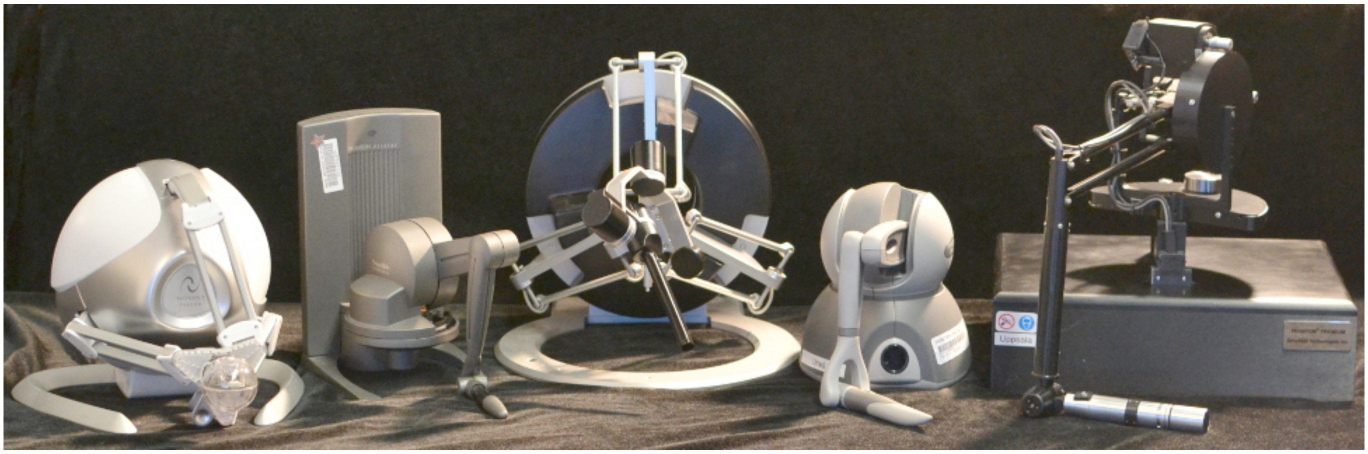

Figure 2. Common spatial haptic devices. From the left: Novint Falcon, Phantom Desktop (now 3D Systems Geomagic Touch X), Force Dimension Omega, Phantom Omni (now 3D Systems Geomagic Touch), and Phantom Premium 6-DOF (now 3D Systems Geomagic Phantom Premium).

In this paper we introduce a new spatial haptic device that is designed and packaged as a kit in a way that a designer can reconfigure or re-design it, thus adapting it to different domains or requirements. This kit, called WoodenHaptics, is designed to provide comparable haptic fidelity to commercial devices. We carefully chose to encapsulate certain technical details (e.g. the electrical system), whereas others are very visible (the mechanical structure and wire rope power transmission); this is intended to help designers focus more on designing for their application rather than problem solving through mechanical and electrical nuances and details. Through these efforts we have reduced the "stickiness" [29] of constructing spatial haptic devices to a level where a designer can design, create, assemble and modify their own version of the device. We evaluated its ease of adoption on non-specialists and first-time builders (under guidance) to show that it provides a valuable medium for "hardware sketching" in spatial haptics.

Background

With the advent of Massie's [10] force-reflecting device in 1993, spatial haptics as a multi-purpose human-computer interaction interface became popular through the commercialized Phantom series [11] still available on the market today (figure 2). 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/movement is quite different, something that is also reflected in the price tag that ranges from $300 to over $20,000 USD. Other devices with equivalent functionality from the user's perspective have since appeared, but the market is far from being as diverse as that of computer mice and joysticks.

A great deal of fundamental theory for building a haptic device has been described in e.g. [7] and [6]. However, bridging the gap from reading the fundamentals to constructing a fully-functional 3D spatial haptic device of the prototypical Phantom [10, 11] is still a daunting task to a common interaction designer and is only feasible for an expert roboticist. Much practical and tacit knowledge is required to actually make a high-fidelity haptic device, since it relates to making a correct combination of design choices, ranging from which type of motors, what mechanical structure, which control paradigm and even which type of screws to choose. 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, 4] might be overwhelming in scope and content to the electro-mechanical novice.

Kits and Tools for Design

Kits and tools for design through making and crafting is an active research area in TEI/HCI [5, 8, 13, 14, 25, 26]. Phidgets [5] is used to simplify development of physical interfaces through providing "everyday programmers" with a kit of premade electronic physical widgets. Toolkits have been described as particularily instrumental to sketching in hardware [19]. Software tools have been developed explicitly targeting designers without production training in electronics [8] and furniture design [26]. Even the notion of an "untoolkit" has been proposed as a conceptual tool to leverage existing standard materials and components in new artifacts [14]. Open source hardware designed for personal fabrication has been described as an approach to support design of different aspects of electronic products, since the designer only has to modify those parts of the design pertinent to the designers interest and still get a working product [13]. Other kits such as the Hapkit [15] is constructed with goal of teaching engineering concepts per se through hands-on experience [21, 27].

In this paper, WoodenHaptics is presented as an open source "starting kit" for material exploration, design and realization of application specific force reflecting haptic devices. This distinguishes our kit from a toolkit where combinations of provided parts yield many designs (we only provide one reference design in the kit itself), and an untoolkit where none of the modules from the kit goes into the final design. The intended audiences for the kit are interaction design studios and HCI researchers, especially for cases where applications require different form factors (e.g. length of arms), and other properties (e.g. maximum force) that off-the-shelf devices won't meet, something we in our own practice have seen a need for. Our primary aim is to support professional design

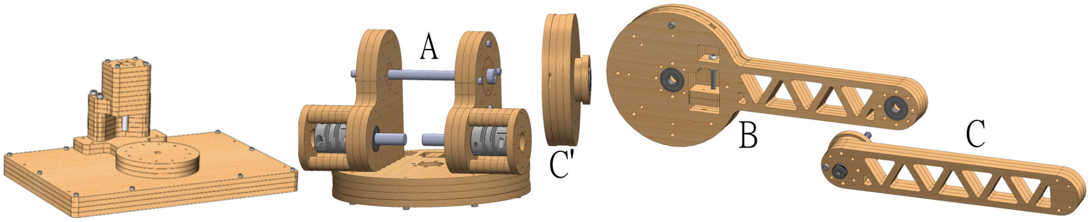

Figure 3. The parts needed to be assembled by user: the base driving the body A, that in turn drives body B and, indirectly through C', body C.

exploration of the interaction qualities that follows from modifications of the reference design. A high-quality spatial haptic interface requires careful attention to its computational and physical materials, which can *only* be experienced as a whole with a fully assembled device. Therefore, a designer who decides to deepen her engagement beyond software will have to set up a workbench for explorations. WoodenHaptics serves as a complete kit for starting such explorations.

PART II: KIT DESCRIPTION AND USAGE

A pair of interaction design researchers without training in mechanical engineering were provided with the kit consisting of a complete set of hardware components that make up a full spatial haptic device. This included all the pre-cut plywood parts, screws, bearings and all other mechanical components (Figure 4). The kit came with three motors (Maxon RE40) with pre-mounted encoders, and an electronics box (Figure 5) that connects to a 48V lab power supply and a standard PC equipped with a Data Acquisition interface (DAQ, Sensoray S826). The kit requires only a limited set of tools: hex keys, a steel wire crimping tool and snippers, a torch and an arbor press (Figure 8); a list of these tools and where to purchase them are available online. Software required to operate the device was included as well. Thus, the builder can immediately run available demo programs and proceed to application-specific development.

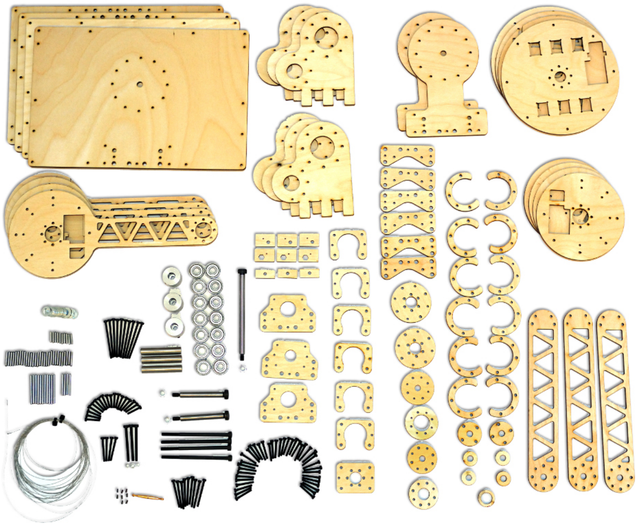

Figure 4. The parts included in the kit. Not shown here are the three motors, electrical cables and the electronics box (Figure 5), and configurable software that completes the kit.

Assembly

The entire structural pieces are manufactured from a laser cutter out of 6 mm (or approximately 1/4 inch) plywood. To form stiff three-dimensional parts from the flat sheets, several layers are stacked and held together with screws. All holes in the plywood parts are adjusted with sub-millimeter 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 disassemble-able and reconfigurable device. The kit comes with instructions on how to assemble the main bodies, as well as video documentation.

The bodies A, B and C (figure 3) form the three links or *degrees of freedom* (DOF) that together enable the tip of the device (P in figure 6) to be moved left/right, up/down and in/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 5).

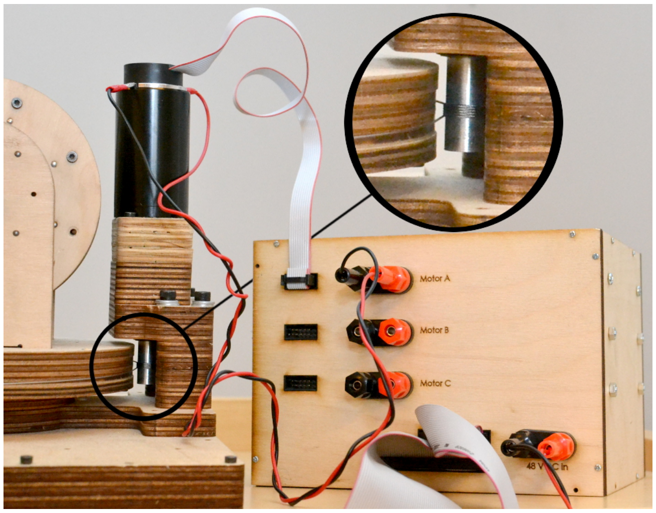

Figure 5. The first degree of freedom motor connected with power and encoder wires to the electrical interface. The close-up view shows the aluminum capstan and wire rope coupling.

Cabling

The kit utilizes cable drive for all its transmissions: a strong steel wire rope transmits the power from each motor to its own respective link. Figure 5 shows a standard cable drive transmission used in all degrees of freedom. The motor shaft is attached to the *capstan*, which is a shaft for a cable to wrap around and grip. The cable makes 5 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 turnbuckle is used to maintain a taut cable. 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 for achieving larger forces without using gearboxes, as well for easy replacement of motors. The reasons for these design choices are further discussed in Part III.

Electrical system

The kit comes with three high-quality motors, each driving a respective degree of freedom. The designer only has to connect the encoder to the electronics box (that routes them to the computer), and each motor power cable to respective output of the electronics box (figure 5). Two ribbon cables connects the electronics box with the Sensoray S826 board on the PC.

The motors chosen are more powerful than is common in the devices pictured in figure 2. They are specified for allowing a max continuous current of 3.16A safely, and we have limited the maximum current to 3 ampere. This means that the user will not have to worry about electrical heat, burning, etc, which is the case when the motors are overdriven in short periods of time, which is common practice otherwise.

Software Configuration

The kit is complete with a working open-source software module for the mechanical design that comes with the kit. If a dimension have been changed by the user or tuning of the experience is desired, the user can easily modify a variable in a text file to represent this change. The variables of interest to change are: the diameter of each capstan and body, the length of each link and 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 the user will then need to adjust the torque/current ratio as defined by their motor datasheet. The maximum stiffness and damping of the complete device can be found retroactively by experimenting and adjusting the values accordingly.

PART III: FUNDAMENTALS AND THEORY

This section describes how the kit was developed and the design principles/considerations involved. We cover here briefly, the mechanical structure, the kinematics and control theory applied and why certain design decisions were made to support easy user fabrication and modification in particular. We are knowingly only addressing one kind of mechanical structure (the serially linked) and one control type (impedance control). Alternatives are parallel mechanical structure like e.g. Novint Falcon, and admittance control [28] that requires force sensing.

Haptic fidelity and transparency

The power transmission of a haptic device is a critical component that needs to be designed carefully as it transmits the forces and velocities from software to the hand of the user. Haptic fidelity is achieved by having *transparency* in the system – that is, desired forces and velocities defined in software accurately match forces and velocities delivered to the user. Three major contributions that reduce the transparency of a system is friction (resulting in diminished haptic perception), backlash (resulting in chatter in the motors and the device), and physical compliance (resulting in a loss of ability to perceive stiff environments).

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 no gearbox can achieve. The choice of cable is also an important factor: a cable with high flexibility will provide greater transparency as the users will not percieve the forces required to “bend” and “unbend” the cable as the capstan rolls. Therefore, uncoated stainless steel cables with high count of individual steel fibers (we use a cable of 0.54 mm diameter, with fibers in a 7×7 configuration, more is recommended if available) present a viable option. The grip of the cable on the capstan increases exponentially as the cable wraps around, and therefore even a few turns will immediately prevent the cable from slipping. In practice, 5 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.

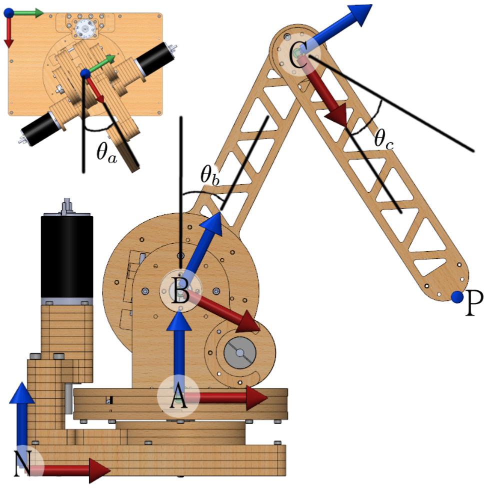

Figure 6. The device is a serially linked mechanism, where the angle of A, B and C uniquely defines point P in the base reference frame N.

Another major design choice for achieving high haptic fidelity was to mount the second and third axis motors on body A (figure 6). This choice is highlighted by three intentional benefits: the simplified and shorter cable routing affords better transparency in the system, placement of the motors allow for easy access, removal, and installation for other motors of different sizes, and shorter cable routing reduces the chance of the transmission de-cabling. Failure in the cable transmission (e.g. cable snap or comes loose) is thereby localized to its own small section of the device, while allowing for the rest of the device to remain in working order.

The third major contribution to achieving transparency in the system is having a physically stiff device. Increasing stiffness (ie. reducing compliance) in the device's structure is done by increasing the second moment of inertia of each link (e.g. making link wider so they do not twist), improving the joint stiffnesses (e.g. by increasing shaft diameters, increasing distance between shaft bearings that hold the shafts straight), and using a stiff material. Because plywood is a layered composite, it is in fact quite stiff and yet 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.

Finally, each motor to capstan combination is connected through a flexible shaft coupler, which acts to not only 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. This serves to promote hardware sketching on the actuator side.

Mathematical description and analysis

In order for the spatial haptic interface to be useful, the position of the user's hand and thus the end-effector of the device must be known in space. This is achieved by measuring the angle of the motor shafts using encoders, and doing the forward kinematics to map motor angles to cartesian-space position. Below we provide only a very brief overview of the mathematics involved in achieving haptic feedback; all the details regarding the position and force mappings discussed in this section are derived from [4] using standard techniques for robot manipulators.We derive the manipulandum position through forward kinematics, which in this case is a classic 'RRR' configuration manipulator; that is, it has three moving links which are serially-linked through revolute(R) joints (figure 6), and can be calculated as follows:

$$\begin{aligned} P_x &= \cos\theta_a(L_b\sin\theta_b + L_c\cos(\theta_b+\theta_c)) \\ P_y &= \sin\theta_a(L_b\sin\theta_b + L_c\cos(\theta_b+\theta_c)) \\ P_z &= \qquad L_b\cos\theta_b - L_c\sin(\theta_b+\theta_c) \end{aligned} \tag{1}$$

where L is the length of each body to the next and $\theta_{a,b,c}$ are the angles of respective body. To give a force $\mathbf{F}$ at the manipulandum, the body torque τ is computed as:

$$\tau = \mathbf{J}^\top \mathbf{F}, \tag{2}$$

where $\mathbf{J}$ is called the Jacobian matrix, and is the first partial derivative of the forward kinematics (1) with respect to the body angles θ [4]. A final necessity to account for is the weight of the manipulandum: without compensating for the manipulandum weight, the user will have to hold up the device's weight in their hands. To compensate for gravity, the weights of the three links as well as their centers of gravity are estimated, and motor torques to counter gravity forces are applied. For ease of use, the kit's software module allow for tuning of the link parameters while masking the mathematics involved to solve for force, position, and gravity.

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 lab quality and should not be confused with hobbyist counterparts. While efforts to replace them with lower cost alternatives are very welcome, one has to be careful in preserving the precision needed. For example, the delay has to be less than 1 ms and the resolution and quality of D/A converter sufficient [23]. However, this also brings to the surface the potentials of this starting kit, as it allows users to explore what their haptic tolerance is for lower-cost alternatives.

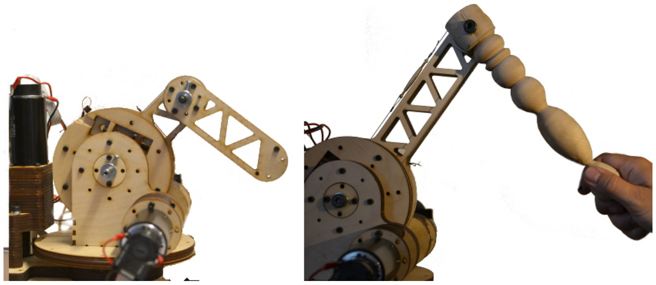

Figure 7. Exploring designs: Mini-woody with smaller workspace and larger forces, and a different handle arm crafted using a lathe.

Variations

While the starting kit provides everything needed to complete a functioning device, the intention is to invite the designer to modification and variants of the design. Below we highlight a few interesting areas worthy of exploration:

Workspace

The user 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 7 depicts a smaller version, that also, as a direct consequence, can render larger forces (table 1).

Motors and Encoders

The user can switch between using high-cost, high-quality motors and encoders, or a 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 $20 hobby shop motor versus a $300 motor). Effects of motor size can also be investigated.

Material

Plastics (such as acrylic) are as easy to cut as plywood, and comes in different colors for the designer to experiment with, but can be brittle. They also tend to be heavier, which have to be supported with more motor torque for gravity compensation. Aluminum is lightweight and stiff, but needs to be cut using special equipment (warter-jet cutter) and requires threading holes separately. Solid and composite wood choice 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 7 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 perception of textures [12]. Different grips or end-attachments that interface with the user can be explored.

PART IV: EVALUATION

Three aspects of the reference design and starting kit were evaluated. First, to what extent could someone without robotics training or access to a sophisticated lab use the kit, assemble the device and make it work? Second, how does the device compare to commercially-produced haptic devices? And finally, what are the technical properties?

Assembly Workshop

In order to investigate the feasibility of the kit, the extent it can reduce stickiness, and the level of instructions required, a workshop was held with two researchers previously inexperienced in robotics construction. While the first version of the device was built in a robotics lab (in the US), this workshop was held in a interaction design lab on another continent (in Europe). All the parts in the kit seen in figure 4 and motors, electronics box and a tool set of hex keys, cable crimper, cutter and arbor press were presented to the users. A computer with the software installed to run the completed device with a virtual environment was provided.

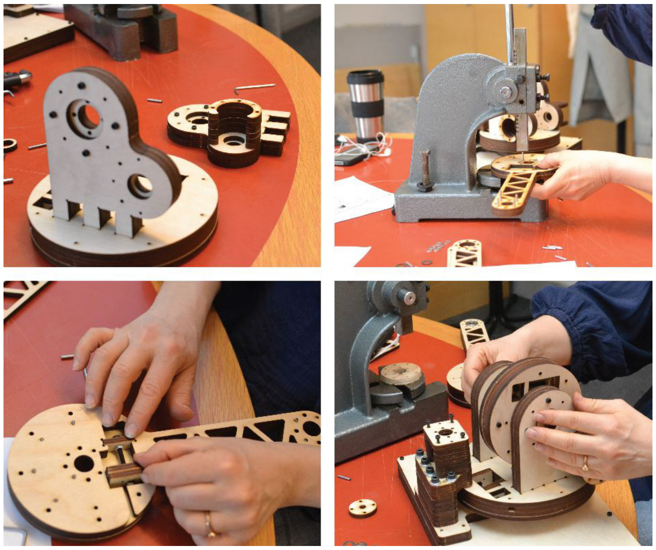

Figure 8. User assembly of the wooden haptics device as part of the evaluation of the feasability of the starting kit.

The instruction material was in the form of print-outs of the bodies with notations of screw location and so on. The users took turns building while being supervised by one of the authors, and guidance was provided when deemed necessary. The assembly sessions were videotaped and notes and build times recorded.

It took the users approximately 11 hours distributed over 4 sessions to successfully assemble the complete WoodenHaptics device. Most of the guidance required was initially regarding the proper use of the tools, order of insertion of pins and screws and so on, and during the process of cabling (the process of mounting the wire rope). These instructions could be readily provided in a detailed construction document as is provided in Lego® sets. Since only one copy of the kit was present and thus some errors would be irreversible, care was taken to make sure stacking of similar parts and assembly order was performed correctly. Despite that, one part got placed in a flipped direction, but could still work in a satisfactory manner. Some bearings were not inserted until parts added later made it cumbersome, and had to be mounted with mallet (with risk of damaging them). Two outer diameters were wrongly adjusted by the authors and had to be reduced with sand paper, since cutting new parts was not an option (no laser cutter in the lab, and long turn-around for ordering). Finally, some extra tools were used: a pair of tweezers during the cabling, and the mallet when the arbor press was too small. With this said, the final device worked as well as the one built previously.

Perceived quality of finished assembly

An evaluation was conducted regarding the quality of the haptic feedback, comparing the Phantom Desktop, Phantom Omni, Novint Falcon and our assembled version of the starting kit, hereafter named "Woody" for short. For this evaluation, 10 participants (5 women and 5 men, mean age 32) were recruited among students and faculty. The same virtual environment[1] was used for each device that were placed side-by-side, which enabled the user to go back and forth between the devices (Figure 9).

Figure 9. The setup of the evaluation showing the four different devices and the demo application used in the test.

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[1] Chai3D version 3.0 example 13 - Primitives, www.chai3d.org

The evaluation consisted of two parts. The participants first task was to rate the experienced quality of the haptic feedback using the devices one at a time. Experienced quality was evaluated in a questionnaire using a seven point Likert-type scale with four items asking about to what degree the haptic feedback felt being of *high quality*, *precise*, *smooth* and *distinct*. In the analysis, the four items were summed into one dimension measuring subjective experience of haptic feedback quality. The questionnaire was filled in after experiencing each haptic device respectively. In the second part, participants compared all devices again and reported which one of the commercial devices they felt most closely matched that of Woody in haptic quality on their own terms.

The results, as the average summed ratings (std. dev.) of each device was as follows. Desktop 25.8 (2.10), Omni 19.5 (5.7), Falcon 11.2 (6.3) and Woody 24.4 (3.37). The participants thus rated Woody's experience between Phantom and Omni. It resonates with the second part of the evaluation when the participants were explicitly asked to draw a line between Woody and the device they thought was most similar to Woody. The results show that 7 of the participants thought that Woody was most similar to the Desktop, 3 reported that Woody felt the most similar to the Omni.

Changing haptic properties when varying design

In order to demonstrate the ability to modify haptic performance through design, different versions of the device were constructed with the starting kit as a base. Woody (B=20 cm, C=22cm) and a "mini" variant (B=10 cm, C=12 cm) were created to explore the trade-off betweeen workspace and force-feedback properties (Figure 7). Stiffness was empirically tuned at a level where no vibrations was felt while interaction were at a maximal stiffness (5 N/mm). The results are presented in Table 1. For comparison, maximum force values for Omni and Falcon were added from [22] and friction and workspace measurements were taken for these devices as well. A lower bound for the workspace was found by placing a virtual sphere in the virtual origin and increasing its diameter while maintaining that the whole sphere can easily be touched from the outside. Peak force was found for Woody and Mini-woody by calculating, but not physically outputting, the largest force that could be applied in x, y, and z direction until at least one motor saturates. The workspace was swept and the lowest value was recorded. Since the motors were specified to handle more than 3 ampere nominally the continuous force and peak force is the same. Back-drive friction was measured using a hand-held digital force gauge (FG-5000A-232, Lutron Electronics, Taiwan) slowly moved from one side of the workspace (as defined above) to the other passing the origin, sideways, inwards and upwards. Ten measurements were taken and averaged for each direction and device. Gravity compensation was enabled if available. Omni, which lacked active gravity compensation was supported by a 2 m thin string from the ceiling in sideways and inwards measurements.

This study demonstrated the exploration of trade-offs in changing workspace dimensions with forces and friction. The commercial devices provided the static performance mark for which the modified designs were compared against. It can be seen that there is no one device that provides the largest workspace, forces, or minimum friction altogether, showing the strengths and limitations of each design and the benefit for hardware sketching.

	Woody	Mini-w.	Omni	Falcon
workspace	200+	80+	100+	60+
peak force	9.9+	19.0+	3.3	8.9+
cont. force	9.9	19.0	0.88	8.9
friction	0.6/0.7/0.9	0.6/1.0/0.9	0.2/0.4/1.1	1.2/3.6/1.3

Table 1. Varying haptic properties through different design changes, and comparison to commercial devices.

PART VI: DISCUSSION

We have shown how the WoodenHaptics starting kit can be an engaging spatial haptics device testbed without many of the sticky issues usually involved in the craft. We have furthermore demonstrated that high haptic fidelity was achievable using WoodenHaptics, on par with commercial devices. For an interaction designer, the WoodenHaptics toolkit serves to:

- help the designer understand the fundamentals of the mechanism (e.g. it shows clearly how three motors work together to generate one force vector at the end point of the manipulandum).
- enable the designer to incorporate the device into their own projects quickly and easily without being a electro-mechanical expert.
- enable the designer to explore the user experience (by objectively changing/tuning certain parameters or replace components such as motors).
- establish a common language between designers and experienced hardware engineers. The designer can now say "can you make a device like this, but smaller?" or "what could or needs to change for us to manufacture something like this for our application?"

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 solving many electrical, computational and mechanical problems since these have already been solved; it instead allows the user to innovate in terms of motor choices, workspace dimensions, physical material, aesthetics and extended functions like buttons. As personal fabrication of parts becomes easier, e.g. through direct interaction with a laser cutter [20] or software tools [26], designers can quickly explore different variations that can optimize their haptic experience for a particular application.

Common haptic devices and application programming interfaces sometimes give wrong expectations of what experiences they actually support. For example, Mousette [17] noted that "hardware hard is relative" from his experiments with a commercial haptic device where a virtual object specified to be of maximum stiffness still yielded a sensation he refer to as "mushy hard". It is likely that he would have had a different experience with a device equipped with more powerful motors, or if the developers had used another terminology than "hardness" to describe the feature. By crafting with WoodenHaptics one can learn, experience, quantitatively define, *and alter* mushiness or other unarticulated haptic experiences.

WoodenHaptics is not intended to replace off-the-shelf devices and is not necessarily cheaper. Instead it offers unique opportunities for dedicated designers as a workbench for exploring the experiential qualities of new designs. The components mentioned here carry a cost of about 3000 USD. Future work, especially on the electronics side, will lead to significantly lower costs (e.g. use of custom circuit board).

Finally, designers are encouraged to share their experiences and designs with the community, and improve upon the kit itself. This allows them to go beyond the original constraints set by the kit and its modules when they are ready. We also expect simpler versions for e.g. 2-DOF planar device to benefit from our modules. Bringing spatial haptic device design to a larger audience allows them to share more perspectives on both what a designs should look like and how they should be evaluated.

ACKNOWLEDGMENTS

WoodenHaptics was initially developed at Stanford University. We are thankful to Reuben Brewer and Ken Salisbury for introducing many of the concepts discussed in this paper in CS235: Applied Robot Design for Non-Robot Designers. We would also like to thank Adam Leeper and Ylva Fernaeus.

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