Title
Spurring Innovation in Spatial Haptics: How Open-Source Hardware Can Turn Creativity Loose

Journal
IEEE Robotics & Automation Magazine, 24(1)

ISSN
1070-9932

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Publication Date
2017

DOI
10.1109/mra.2016.2646748

Peer reviewed

Turning Spatial Haptics Into Open Source Hardware

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***Abstract*—This paper discusses WoodenHaptics, an open-hardware robotics kit for designing spatial haptic interfaces. The kit, which has been made available free-to-download online, enables interaction designers with little electro-mechanical experience to manufacture and assemble a fully working spatial haptic interface. This paper describes a history of the project, the mechanical principles for high fidelity haptic rendering, the mathematical foundations of the device, and bill of materials. A particular focus of this paper is on what steps have been taken to ensure a design that is easy to replicate and modify while being as cost effective as possible without losing the precision required for high-fidelity force-reflecting haptic feedback. Results from an interview study with initial external users will be 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 towards replication elsewhere.**

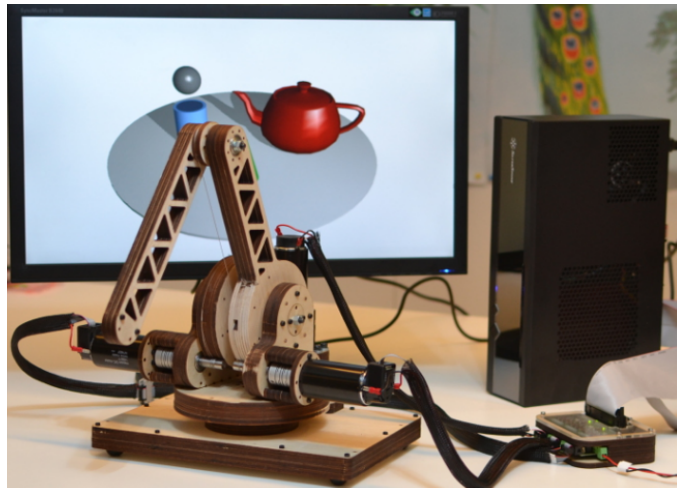

Fig. 1. The complete, open-sourced WoodenHaptics toolkit.

I. Part I: Introduction

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 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 90's, has yet to reach 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 paper discusses our efforts to overcome the construction challenges through the open source starter kit called *WoodenHaptics* (Figure 1), a 3-DoF haptic device conceptually similar to the Phantom, packaged as an open-hardware and open-software starting kit for design explorations. First introduced in 2015 [3], WoodenHaptics follows the philosophy of *sketching in hardware*[4], where subsystems are carefully formed that 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 quickly explore physical variations of a design in a hands-on fashion, thus focusing on designing for their application rather than problem-solving through mechanical and electrical nuances and 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, but it is not necessary for most applications. Through these efforts, we have reduced the "stickiness" [5] of constructing spatial haptic devices to a level where a designer can design, create, assemble and modify their own version of the device. A major focus of this paper is on what steps have been taken to ensure a design that is easy to replicate and modify while being as cost effective as possible without losing the precision required for high-fidelity force-reflecting haptic feedback. Furthermore, a collection of variations on the design from different users, as well as user experiences, are compiled.

A. Background

With the advent of Massie's force-reflecting device in 1993 [2], spatial haptics as a multi-purpose human-computer interaction interface became popular through the commercialized Phantom series 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.

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 micro-surgical bone drilling [6]. However, engineering a haptic device is 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. Without adaptation of the device hardware, there is a fundamental limitation on the quality of the haptic rendering for a particular application [7]. Thus, for more widespread adoption and innovation of spatial haptic

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Manuscript received June 5, 2016.

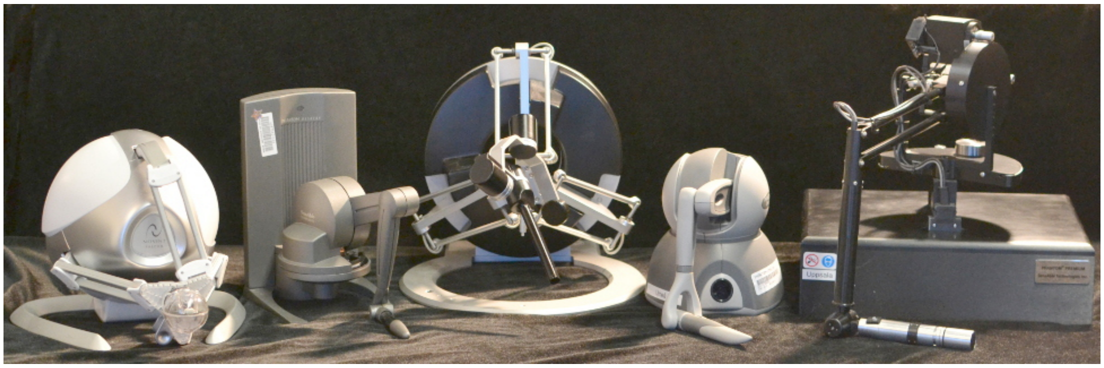

Fig. 2. Common spatial haptic devices. From the left: Novint Falcon, Phantom Desktop (now 3D Systems Geomagic Touch X), Force Dimension Omega, Phantom Omni (now 3D Systems Geomagic Touch), and Phantom Premium 6-DOF (now 3D Systems Geomagic Phantom Premium).

devices, algorithms, and applications, this inaccessibility of haptic device design and its 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 e.g. [8] and [9]. However, bridging the gap from reading the fundamentals to constructing a fully-functional 3D spatial haptic device of the prototypical Phantom [2] is still a daunting task to a common interaction designer and is only feasible for an expert roboticist. Significant 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 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 [8] may be overwhelming in scope and content to the electro-mechanical novice.

1) Kits and Tools for Design: Kits and tools for design through making is an active research area [10], [11], [12], [13]. A successful translation of this effort is Phidgets [10], used to simplify development of physical interfaces through providing "everyday programmers" with a kit of pre-made electronic physical widgets. Toolkits such as Phidgets have been described as being particularly instrumental to sketching in hardware. Software tools have been developed explicitly targeting designers without production training, such as in electronics breadboarding [11]. Even the notion of an "untoolkit" has been proposed as a conceptual tool to leverage existing standard materials and components in new artifacts [12]. 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 valuable in workshops by Mellis et al [14].Currently, the other notable haptic toolkit currently maintained is the Hapkit [15], a 1-axis paddle for force feedback that is constructed with the goal of teaching engineering concepts through hands-on experience.

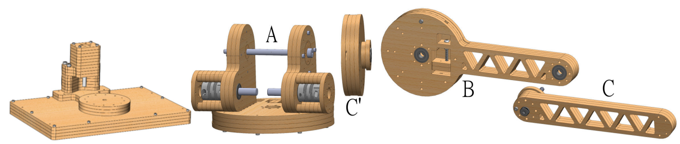

Fig. 3. The parts needed to be assembled by user: the base driving the body A, that in turn drives body B and, indirectly through C', body C.

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 non-expert roboticists interested 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 meet, something we in our own practice have seen a need for.

II. Part II: Kit contents, fabrication and usage

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 included all the pre-cut plywood parts, screws, bearings and all other mechanical components (Figure 4). The kit is completed with three motors (Maxon RE45) with pre-mounted encoders, and an electronics box (Figure 6) 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 cutters, a torch and an arbor press (Figure 10); a list of these tools and where to purchase them are available online. Software required to operate the device is included as well, in the form of an extension to the open-source haptics API Chai3D 3.0. Thus, the builder can immediately run available demo programs and proceed to application-specific development.

The non-standard 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

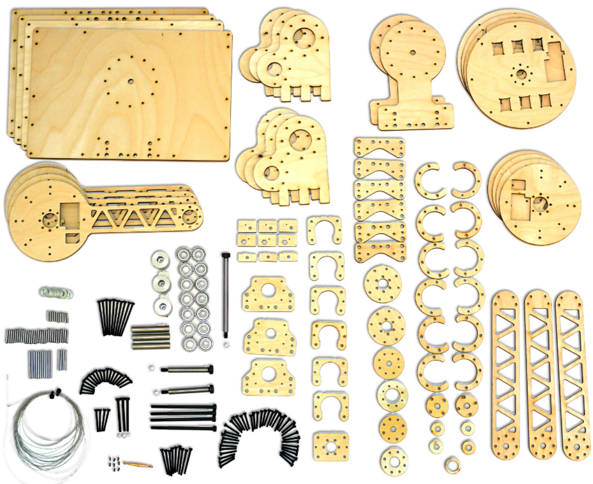

Fig. 4. The parts included in the kit. Not shown here are the three motors, electrical cables and the electronics box (Figure 6), and configurable software that completes the kit.

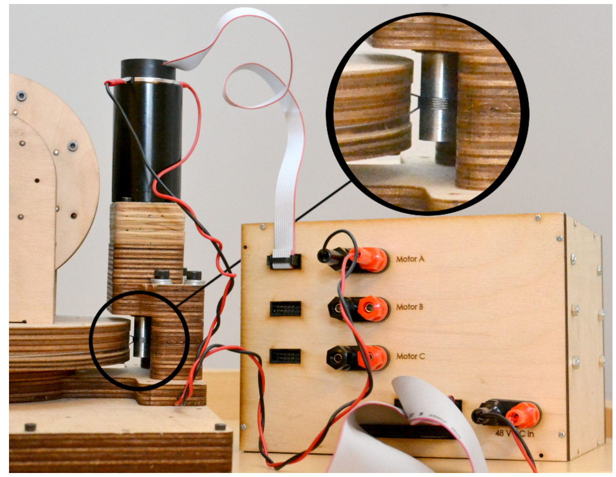

Fig. 5. The first degree of freedom motor connected with power and encoder wires to the electrical interface (of the early non-PCB-based version). The close-up view shows the aluminum capstan and wire rope coupling.

thus digital in the form of order-ready laser-cut flat sheet vector drawings, printed circuit board layouts, and a spreadsheet of parts with suppliers. The underlying design files, i.e. CAD models and circuit schemes are available as well for those interested in modifying a specific module.

A. Assembly

The entire structural pieces are manufactured from a laser cutter out of 6 mm plywood sheets. 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 located 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 7) 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).

B. 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 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 discussed in Part III.

C. Electrical system

The kit specifies 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 the respective output of the electronics box (figure 5, 6). Two ribbon cables connect the electronics box with the Sensoray S826 board on the PC.

Using a custom Printed Circuit Board, PCB, (figure 6) even when it is only handling routing of wires, has the benefit of avoiding loose cables, easy of replication and makes 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 using the flexible but more expensive DAQ, or attaching a easy-to-use microcontroller (mbed LPC1768, 96MHz 32-bit ARM Cortex-M3) that connects to the computer over USB. Having the option can cater for different communities. Application designers may prefer the plug-and-play readiness and lower price of USB (currently in beta), where as robotics researchers may desired DAQs for low-level signal processing and controls.

The motors chosen are more powerful than is common in the devices pictured in figure 2. They are specified for allowing

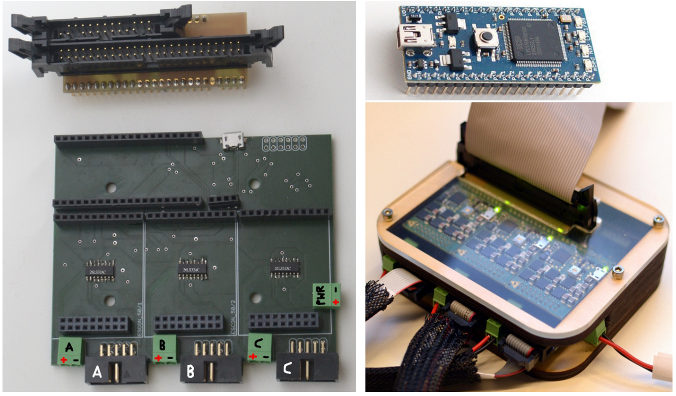

Fig. 6. The PCB-based electronics box used as an intermittent between the motors/encoders and the PC/DAQ. The custom-made "motherboard" houses three current driver modules and can be equipped with an attachment for DAQ connection (default, top left) or an mbed-compatible microcontroller platform (top right).

a max continuous current of 3.16A safely, and we have limited the maximum current to 3A. 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.

D. *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 has been changed by the user or tuning of the experience is desired, the user can easily modify a variable in a JSON-formatted text file to represent this change (Table I).

TABLE I
MODIFIABLE JSON SCRIPT DESCRIBING THE DEVICE

```
{                                             Unit
  "diameter_capstan_a":         0.01,        m
  "diameter_capstan_b":         0.01,        m
  "diameter_capstan_c":         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,      A (see motor datasheet)
  "torque_constant_motor_b":    0.0603,      A
  "torque_constant_motor_c":    0.0603,      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
}
```

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 specified in their motor datasheet. 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 [16], and is easily ported to other API's such as H3D [17] (since it only depends on a few calls to the DAQ card's C-library).

III. PART III: FUNDAMENTALS AND THEORY

In this section, we will describe the following: (1) the fundamental electro-mechanical 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.

A. *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 in-perceivable (a.k.a. transparent) to the user. Formally, a transparent system is one where the transfer function between the desired input and the system output variables (usually forces and velocities) comprises only a gain term. If the gain is 1, then forces and velocities exactly replicated. 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 was designed to maximize the haptic transparency of the system by minimizing the following non-idealities: 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 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. Each motor is mounted in such a way such that their motions are decoupled from the motions 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, placement of the motors and motor couplings 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. Independent axis control also means that failure in the cable transmission (e.g. cable snap or comes loose) in one axis does not affect (de-cable 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, 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 stiffness of the transmission and reflect high stiffnesses. At the same time, a ultra-flexible 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 $F_{grip} = e^{\mu\theta}$, 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 higher coefficient of friction and therefore we attain high grip forces with aluminum and steel. 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.

Device Compliance: 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, is unlikely to split, 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. Increased stiffness can be achieved by using other materials such as aluminum (which could be cut into sheets using a waterjet cut rather than lasercut) can result a stiffer device, and in fact lighter as well (density of 6061 aluminum is 2700 kg/m^3 as compared to baltic birch plywood at approximately 3500 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 press-fits of bearings and finger joints.

B. Mathematical description and analysis

The haptic device is displayed in a virtual environment as a point (avatar) in the virtual environment and whose location is determined via a forward-kinematics representation. The forward kinematics is defined as $f(\theta)$ where $\theta = \{\theta_a, \theta_b, \theta_c\}$ is a vector of the joint angles. In this case, the manipulandum

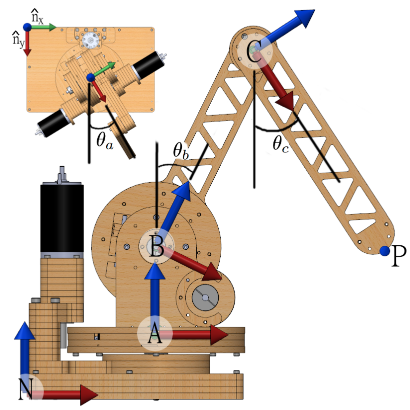

Fig. 7. The device is a serially linked mechanism, whose base are fixed in a reference frame $N = \hat{n}_x, \hat{n}_y, \hat{n}_z$. The *position* communicated from the device is defined as the vector $\vec{r}$ from base frame origin N to the point P, located at the end of body C. The vector can be found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

is in the form of a classic 'RRR' configuration manipulator: three moving links which are serially-linked through revolute (R) joints (Figure 7). However, because 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:

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

where L is the length of each body's center of rotation to the next. The forward kinematics is also used in identifying the device Jacobian matrix $\mathbf{J}$,

$$\mathbf{J} = \begin{bmatrix} \frac{\partial f}{\partial\theta_a} & \frac{\partial f}{\partial\theta_b} & \frac{\partial f}{\partial\theta_c} \end{bmatrix} \quad (2)$$

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

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:

$$\tau = \mathbf{J}^\top\mathbf{F}, \quad (4)$$

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 $\dot{\theta}$ be the rotational velocities of the system, then

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

It can be seen here how non-idealities 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, the user will have to hold up the device's weight in their hands. To compensate for gravity, the mass of the last two links as well as 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 τ_g are:

$$\tau_g = g \begin{bmatrix} 0 \\ m_B l_b \sin\theta_b + m_C(l_b + l_c)\sin\theta_c \\ m_C l_c \sin\theta_c \end{bmatrix} \tag{5}$$

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 $k_i = d_{\text{pulley,i}}/d_{\text{capstan,i}}, \quad i = 1..3$. Then, 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 $\mathbf{i}$ to drive to each motors is $\mathbf{i} = \mathbf{K_c}^{-1}\tau_m$.

C. 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. 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.

D. 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:

1) 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 8 depicts a smaller version, that also, as a direct consequence, can render larger forces (Table II).

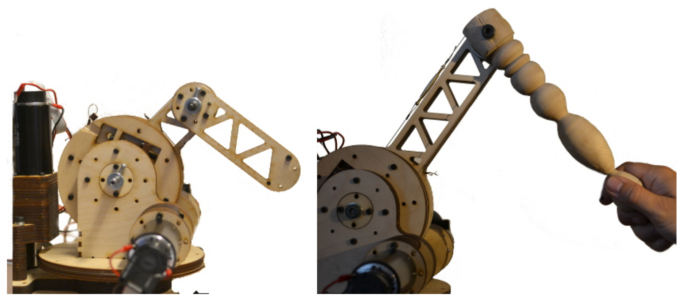

Fig. 8. Exploring designs: Mini-woody with smaller workspace and larger forces, and a different handle arm crafted using a lathe.

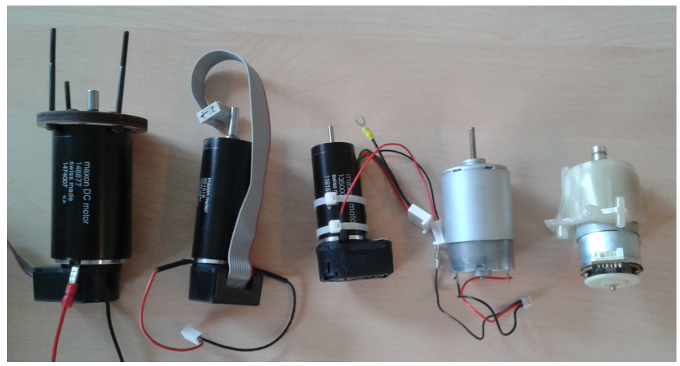

Fig. 9. Different motors that have been used for haptic devices, from left: Maxon RE40, Maxon RE30, Maxon RE25 (Phantom), Mabuchi RS-555PH (Falcon), Mabuchi RS-455PA (Omni)

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 \$20 hobby shop motor versus a \$300 motor). Effects of motor size can also be investigated. Figure 9 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 that there is *no* cogging torque and so that the manipulandum feels smooth to operate. For low cost devices such as the Novint Falcon, anti-cogging 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 [18].

3) 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 (water-jet cutter) and requires threading holes separately. Solid and

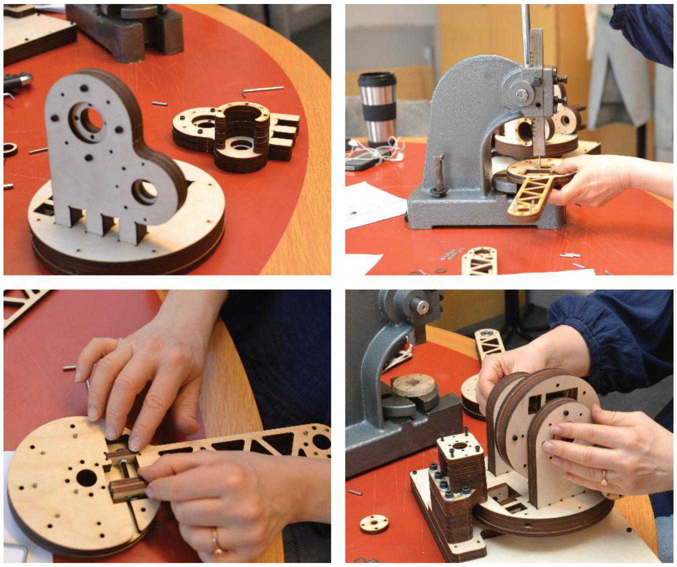

Fig. 10. User assembly of the wooden haptics device as part of the evaluation of the feasibility of the starting kit.

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 8 shows a variant where one part is hand-fabricated from solid wood using a lathe.

4) Add-ons: A user may add buttons, sensors or even vibrotactile actuators on the manipulandum, which can further improve the perception of textures [19]. Different grips or end-attachments that interface with the user can be explored.

IV. Part IV: Community Reception

Our previous studies 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 Phantom Desktop, the most expensive device in the test. It was also shown how it was possible for a non-engineer to assemble the device, under supervision, using a limited set of tools in an ordinary office environment [3]. The assembly (Figure 10) took 11 hours stretched over a few sessions.

In order to evaluate the early community reception of WoodenHaptics an interview study was carried out with total of 7 subjects (male, aged 23-48 avg. 32 years, representing four different nationalities) that had either built the device on their own or recently made inquiries on the woodenhaptics website. Two interviews were made in person, and three over video link, of which one was a group interview with three subjects. All participants were informed of their voluntary engagement and gave their consent to recording for confident analysis by the researchers. A semi-structured interview protocol was used and each interview lasted 30-60 minutes. Notes taken during the interviews and the recordings was partly transcribed and analyzed and sorted into themes.

Two of the respondents, who both were professional engineers but with different backgrounds, had built the device, one using plywood and the other using acrylic. One was a professor who had shown interest in using the device primarily for teaching of mechatronics and controls. A fourth was a Masters student in HCI with non-engineering 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 experience of building physical things to various degrees.

A. Results

The results of the interviews can be sorted in; motivation, including both those who built it and those who have expressed an interest in doing so, and the building experience regarding sourcing components, manufacturing and assembly.

1) Motivation: While the number of respondents in this study was low they represented a wide spectra in terms of motivation for building their own WoodenHaptics device. The two who had already build one wanted to produce a public display tech demo, showing their corporations technology along with haptic remote control. They mentioned having control over all aspects of the technology as well as the ability to render high stiffness and forces as important factors. The HCI student got interested in haptics after a visit to a surgery simulation facility and wanted to explore it further without a particular application in mind:

> "I really like the look and feel of the product. It got this craft feel to it. Its not like a final product, you know totally refined and built in a factory somewhere [sic]. 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, Im curious about it."

The professor thought the device would suit their education style well, suggested that depending on course you may exclude or include moments of the building experience. For example a electronics class may design and make their own H-bridge, but have the rest given, or vice verse.

2) Sourcing of components and parts: The corporation in the study sourced components themselves using the suggested suppliers, except for the variant in acrylic that was sourced from a local laser-cutting supplier. They had no preference on sourcing parts from one or several suppliers. The same can be said for the mechatronics students, for which it was part of the learning experience to research alternatives and source parts. However for the self-directed HCI student, who also currently was living abroad, the sourcing of parts from various vendors was identified as a big obstacle and he would have preferred getting everything as a kit. The professor expressed appreciation for a possibility to source and manufacture independently using the open source drawings, as well as buying pre-made modules and devices or kits.

Sourcing of parts was successful but not without friction. Taking laser-cut parts aside, some issues include suppliers sending the wrong cable than ordered, some components deprecated and needed to be substituted, a few parts missing from Bill of Materials, and DAQ card with non-default jumper configuration. Receiving all parts unsorted was reported a bit overwhelming at first.

3) Manufacturing: Laser-cutting and making PCB: The respondents, who lacked access to their own laser-cutting machine, used an online service for getting the laser-cut

TABLE II
COMPARING WOODENHAPTICS STARTER KIT TO COMMERCIAL DEVICES

	WoodenHaptics	Mini W.H.	Omni	Falcon	Unit
Workspace*	200	80	100	60	mm
peak force	9.9	19.0	3.3	8.9	N
contin. force	9.9	19.0	0.88	8.9	N
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	N

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

plywood parts, including the material, and a local company for acrylic. They reported several issues before achieving success:

- The plywood had various thicknesses between orders, 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 resulted once in mm 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 less thickness, and as straight cutting as possible eventually proved successful. Also the fact that changes was 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 wrong direction. He found it useful to have ordered spare parts and PCBs for these kinds of mistakes.

4) Assembly experience: The first respondent assembled the device independently, except 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 built up the tacit knowledge of how to do it, using tricks with tape, tension and cutting in the right order etc, and could pass on this knowledge when supervising the next builder. He found using CAD software (SolidWorks) useful for visualizing the assembly, but noted 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 being more difficult to assemble due to its brittleness.

Something that the respondents would have preferred that the components, both laser-cut parts and metal parts, were sorted into bags according to which body they belonged to. While laser-cut parts were originally placed on different sheets, minimizing material waste by combining all the parts on a small number of sheets was done in the cutting process.

V. PART V: 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. It serves to:

- help users understanding the fundamentals of the mechanism (e.g. it shows clearly how three motors combine to generate a force vector at the end of the manipulandum).
- enable users to adapt the device into their projects easily without being a electro-mechanical expert.
- enable exploration of the user experience (changing/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 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 or software tools, designers can quickly explore different variations that can optimize their haptic experience for a particular application. Morimoto et al.'s Hapkit, as an alternative, uses a single variation of the 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 give wrong expectations of what experiences they actually support. For example, Mousette [20] noted that "hardware hard is relative" from experiments with a commercial haptic device where a virtual object specified to be of maximum stiffness still yielded a "mushy hard" sensation. It is likely that the 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 "mushiness" and other difficult-to-articulate haptic experiences.

A. Designing for open-source

As been reflected in the interview responses has the community members different motivations and interest in the building process. Therefore is it essential to enable the 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, in 2D vector graphics software and after fabrication using carpentry hand tools. The ability to engrave text on parts could be used to assist sorting of parts to their logical sub-assemblies, i.e. the bodies A,B,C of the WoodenHaptics device. A challenge for the stacked plywood method is the variance in quality and thickness of plywood sheets, and the variance in the precision of the cuts, especially if a service provider is contracted. However, the existence of internationally shipping laser-cutting firms that can repeatedly reproduce a design within tolerances can be a key to wider dissipation and share of different designs within the community. For WoodenHaptics, we have uploaded the exact files and manufacture instructions used for a successful order of laser-cut plywood and PCBs.

Providing a complete bill of materials including exact choice of default components and internationally shipping suppliers

TABLE III
SOURCING OF THE COMPONENTS

Category	Item	Description	Suppliers	Approx. Cost**
Mechanical Components				
Structure	Plywood	6.0 mm thick baltic birch 5-ply (four 600× 600 mm sheets)	Cutlasercut.com (UK), local lumber yard*	€180 (w/ cutting), €35 (material)
Fastening	Screws, dowel pins, shoulder bolts, nuts, washers	Fastening for Assembly	Misumi (International), McMaster-Carr (USA)*, local hardware store*	€40
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)*	€150
Cabling (wire-rope)	0.54mm flexible stainless steel wire rope, double ferrule, miniature turnbuckle	Cable for mechanical power transmission and fastening	Tecni-Cable (UK), Hobbykellershop (DE)***, McMaster-Carr (USA)*	€20 (tools +€70)
Electrical Components				
Motor	Coreless DC motors (Maxon RE45 default)	High-quality, zero-cogging motors	Maxon, Faulhaber*	3x €400
Encoder	Optical Encoders	Angle sensing at each motor shaft	US Digital (USA)* or pre-attached to motor (Maxon, Faulhaber)*	3x €70
Motor Driver	Current/torque control motor driver (ESCON 50/5)	Embedded solution for current control	Maxon (international), Copley (USA)*	3x €150
Electronics box	PCB, connectors and cables, mounting screws, differential decoder, power supply	Failsafe routing of connections without use of breakouts or breadbord	Farnell (International)	€220**** (PCB), €50 (parts), €150 (PSU)
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*	€800, €500+*, €52*

*Alternative supplier not in WoodenHaptics Bill of Materials. NOTE: The complete list can be found on the project's website; **all prices in Jan. 2016 EUR; ***for miniature turnbuckle *spannschloss*; ****minimal economical order including extra PCBs.

is important to allowing the user to choose when to go for the default and when to substitute and do the necessary adjustment to retain compatibility with the rest. The sourcing process could be further assisted through open hardware facilitating companies providing complete physical kits or modules.

The WoodenHaptics project is maintained at: http://www.woodenhaptics.org.

VI. ACKNOWLEDGMENTS

The authors would like to thank Reuben Brewer and Ken Salisbury (Stanford University), Adam Leeper (Google), François Conti (Force Dimension) and Jordi Solsona (KTH) for their assistance and insight in the formation and development of this project. We also thank Eva-Lotta Sallnäs Pysander (KTH) for supporting the project.

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