Toward Open-Source Portable Haptic Displays with Visual-Force-Tactile Feedback Collocation

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Abstract—Platforms capable of generating a rich haptic feedback are usually quite expensive and under strict proprietary protection. In addition, most of them are not portable and do not deliver a fully integrated force, tactile and visual user experience. In an attempt to break through these limitations, we have created the Haplet: an open-source, portable and affordable haptic device with collocated visual, force and tactile feedback. The triple collocated user experience is delivered by a small-form parallel robotic arm that features a simple vibrotactile actuator at the end-effector. The robotic arm is optically transparent and is motorized at the base where it clips onto a tablet or computer screen. All the electronic components are encapsulated in a custom designed board based on the Arduino Due microcontroller. This board interfaces computer software to the Haplet’s hardware with a capacity of up to four motors and encoders and two vibrotactile actuators. This paper describes our ongoing research on developing the Haplet; and, reports our initial experimental results on quantifying the effect of visual-force-tactile feedback collocation on the users experience and performance.

I. INTRODUCTION

Our interaction with computers and digital worlds is mostly limited to keyboards, mice and more recently flat passive touch surfaces. By adding the feeling of forces and tactile clues, haptics can break this limitation and provide an extremely more natural way of interaction. In certain fields, this has been put to practice. For example, graphic designers use force feedback-enhanced 3D mice to sculpt an organic shape out of simulated digital clay [1]; and, surgery students use state-of-the art haptically-enabled medical robots to feel palpation and cutting of simulated body tissues before working on a real body [2]. Most other peoples experience in haptics, however, is limited to only some vibrations of a smartphone or a gaming controller. In other words, although haptic devices appeared in the market in early nineties, only a subset of the aforementioned challenges. In the following, we first give a brief overview of the available literature on these topics; and then, propose our own contribution toward a more democratized and user-relevant future for haptics.

A. More Accessible Haptics

Among force feedback devices with an average cost of several thousand dollars, the few hundred dollar Novint Falcon [4] represents a singular example that achieved some consumer-level status owing mostly to its affordability and simplicity. Mostly geared toward gaming and proof-of-concept research, the Falcon still lacks one of the main ingredients of being truly democratic, i.e. being open-source. Open-source hardware and software are quickly becoming a disruptive and attractive paradigm. The Stanfords Hapkit, a.k.a. the Haptic Paddle [5], is one of the first examples in force feedback haptics. The Haptic Paddle is an efficient educational tool, but is too simple for representing a haptic human-computer interface. There are few other examples that have attempted to resolve this issue. The wooden haptics project [6], for example, features force feedback devices with more degrees of freedom. The Tpad project, on the other hand, offers a standard accessible tactile platform and has proven useful for fueling creativity in contexts such as student challenge competitions [7]. Our Haplet project at McGill University is intended to contribute further in these directions.

B. Collocated Visuo-Haptic Feedback

Visuo-haptic collocation increases immersion and presence in virtual reality by reducing visuospatial ambiguities and increasing physical intuition [8]. In certain applications that deal with complex visuo-motor tasks, collocation has a direct influence on performance [9]. Dental training simulation is a good example in this context [10]. Despite being expensive and high-end, only a limited number of the existing platforms produce a realistic feeling of visuo-haptic collocation [11]–[13]. This is achieved by either half-

1) Haptics is a non-democratized technology. Platforms that are capable of generating a rich haptic feedback are quite expensive and under strict proprietary protection. This limits the number of people that get to learn about haptic technologies, and limits the pace of innovation.

2) Most of the current haptic platforms are not very practical from a users point of view. Except for some wearables with very limited haptic features, most devices are bulky and non-portable. In addition, they usually do not recreate a very convincing user experience. The latter might be due to a lack of proper simultaneous elicitation of kinesthetic and tactile clues [3] and a lack of natural integration with the users visual experience.

Up to the authors knowledge, most haptic solutions tackle only a subset of the aforementioned challenges. In the following, we first give a brief overview of the available literature on these topics; and then, propose our own contribution toward a more democratized and user-relevant future for haptics.

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mirror display platforms or the more recent see-through head mounted displays (HMDs). See-through HMDs are found to be superior solution [14] for a greater variety of applications including industrial process training [15] and painting [14]. The planar case with a simple haptic device super-imposed on a flat screen is a very interesting special case. In this case, the virtual objects can be easily and seamlessly rendered beneath the user’s hand and the device. Despite this simplicity, there are few examples that study such a case. Ref. [16] presents a cable-driven force feedback mechanism in this context. In this paper, we suggest a more portable solution based on a simple parallel mechanism which also adds tactile feedback.

C. Integrated Force and Tactile Feedback

Fontana et al. [3] present a very good survey of the force-tactile integration problem and its challenges. According to this paper, the mechanical architecture of an integrated force-tactile haptic system, in its most complete form, has four components: a kinesthetic device, a large shape display (large curvature of objects), a small shape display (details that generate variations in the pressure distribution on the fingertip) and a tactile display. A force-tactile display should have at least the first and one of the two last components. Different examples of this generic architecture have appeared in the literature. For example, the device presented in Ref. [17] has the first and third components. Sato et al. [18], on the other hand, improve shape distinction by kinesthetic-tactile integration; while, Wagner et al. [19] suggest consideration of finite element models in the integrated design. Hasser and Daniels [20] discuss a tactile thimble mounted on a Phantom device. Magenat-Thalmann et al. [21] discuss the HAPTEX Project that use an exoskeleton-type of device with tactile components, very similar to [3]. The latter is an interesting project because it discusses the fabric and textile rendering applications. In such applications, using integrated force-tactile feedback is really necessary. Govindaraj et al. [22] discuss a planar setup in this context. The Haplet device presented in the current paper is conceptually similar, but instead of a serial arm, features a parallel mechanism that is optically transparent in order to be mounted on a computer screen and features visuo-collocation and portability.

D. This Paper’s Contributions and Organization

In an attempt to break through the aforementioned limitations, we have created the Haplet: an open-source, portable and affordable haptic device with collocated visual, force and tactile feedback. The triple collocated user experience is delivered by a small-form parallel robotic arm that features a simple vibrotactor actuator at the end-effector. The robotic arm is optically transparent and is motorized at the base where it clips on a tablet or computer screen. All the electronic components are encapsulated in a custom designed an open-source board based on the Arduino Due microcontroller. The next section explains the mechanical design, the mechatronics and the software components of the Haplet. Section III, on the other hand, attempts to quantify the effect of triple collocation on the user experience and performance. Section III.A, in particular, reports a set of experiments for comparing the user’s performance with and without visual collocation; while, Section III.B reports user’s perception studies on texture rendering.

II. HAPLET: AN OPEN-SOURCE PORTABLE HAPTIC DEVICE

The initial work done by Morimoto and Okamura [5] to develop a haptic learning tool that was widely accessible and open-source paved the way for haptics enthusiasts to learn about the technology without the prohibitively expensive costs associated with traditional devices. The Hapkit and associated Haptic Paddle allow users to build different haptic effects using a 1-DoF device. The mechanism hardware, 3D models, electronic hardware, and associated software are all available to the public.

This open-ness, coupled with the recent proliferation and corresponding reduction in costs of home manufacturing tools (laser cutters, 3D printers, injection moulds) has allowed thousands of people to explore the field of haptics that otherwise never would have. This democratization of the technology will only lead to an accelerated advancement of the field as more and more people are exposed to the capabilities and limitations of the current technology.

We have expanded on the work of the Hapkit and Haptic Paddle by building an open-source design that provides higher degree of freedom force-feedback and vibro-tactile functionality and improved communication between the device and other portable technologies. We refer to the new device design as the Haplet as it allows users to couple a force-feedback device with their tablet or laptop displays providing a collocated visuo-haptic display. We believe that this design can more closely replicate the reality of the way we interact with the physical world with our hands.

A. Mechatronics and Electronics

The Haplet board was built based of the Arduino Due. This architecture, much like the Hapkit, was selected to allow for backwards compatibility with many of the existing Arduino shields and board add-ons that are already in the hands of many makers and hobbists. However, the Arduino Due is built around a much more powerful Atmel SAM3X8E ARM Cortex- M3 Processor. The processor has an 84 MHz clock, a native USB OTG capable connection, and two built in DAC ports which all improve the haptic capabilities of the Haplet.

These added functionalities are beneficial as they allow the Haplet to run at much higher speeds, act as a USB host and exchange data with many tablet and mobile devices, and directly render vibrotactile effects.

The native USB port also allows the Haplet to communicate with external devices serially at rates much higher than those possible through the programming port found on other popular Arduino hardware (Arduino Uno, Arduino Mega). The data throughput is limited on these boards as a result of the USB-to-serial converter. Practically, we were able to achieve average rates of data transmission without missing
a time-step for 10,000 iterations up to 5.26 kHz with with a lower bound of 1.7 kHz. For comparison, using the same code and the USB-programming port we averaged a rate of 357 Hz with a lower bounded rate of transmission at 148 Hz.

B. Mechanical Design

The board also features two built in L298 motor drivers rated at up to 46 V and 2 A per phase which allow the operation of up two four motors. Four motor ports are built into the board to allow for the use of standard 6 pin motor and encoder configurations. This means the board can be used to drive multiple single or two DoF devices or up to a single four DoF device.

The design used in this study is based on the 5-bar mechanism. It is comprised of four optically transparent links connected to two ESCAP 16 coreless DC motors. The 3D models and mechanism designs are all being made available online.

The motors here are geared at a ratio of 27.1:1 which greatly increases the perceived inertia of the mechanism. The backlash inherited by these motors also poses a problem as, given the current mechanism configuration the spatial resolution at the end-effector suffers reasonably from hysteresis as the user switches direction.

Despite these downsides we feel the cost of roughly $13 USD per motor through online retailers, an encoder resolution of roughly 0.0259°\(^1\), the high-torque output and low current draw, make these motors highly suitable for a low-cost force-feedback haptic device.

C. Software

Additionally, we are implementing means of communicating between the Haplet and engineering toolsets. We have already developed crude API’s in C++ and Python to integrate the Haplet with computers and tablets.

An additional Simulink block-set was created to interface with the Haplet and allow for use of the device with Matlab’s Realtime Windows Target. This is a powerful tool for such an accessible device as it allows researchers to quickly develop and test ideas. All the subsequent research in this paper was developed using these tools.

III. FEEDBACK COLLOCATION

The following section detail our preliminary investigations into the importance of collocation/integration and user perception studies.

A. Visual and Haptic Feedback Experiments

There exist only a few robust theoretical and quantitative tools to evaluate the interactions between human and computers. The technique which has withstood the most scrutiny over the years is known as Fitts’ Law [23]. Fitt’s applied tools from information theory [24] to Human Computer Interaction (HCI) to evaluate the relationship that models speed and accuracy trade-offs in targeted movements by a human user as a logarithmic relationship.

There has been a large body of work devoted to the study of varying applications and extensions of Fitts’ law [25]–[28]. Accot and Zhai expanded the scope of Fitts’ law as a tool for HCI evaluation by adapting it for various movement tasks such as crossing and steering [26], [27], [29]. Thus the Law of Pointing(Fitt’s Law), the Law of Crossing, and the Law of Steering constitute a basis for the Laws of Action [29] that comprise a tool-set by which we can better quantify HCI interaction. These laws find a linear relationship between the time it takes to complete a task and the difficulty of the tasks in the form of:

\[ T = a + b \times ID \]  

The most widely used implementation of Fitts’ law is referred to as Shannon’s variation in reference to the law’s close ties to information theory.

\[ T = a + b \times \log_2 \left( \frac{A}{W} + 1 \right) \]  

It is used to characterize one dimensional pointing tasks which are common to many human input devices such as the

1Backlash, however, decreases the actual resolution.
computer mouse. An analogous law exists for 2D maneuvering tasks. These are called steering tasks. In steering tasks users are asked to manipulate a tool through a finite width channel from a start point to and endpoint along some path length. A steering task can be interpreted as an infinite series of individual pointing tasks [27], one after another and thus can be represented as:

\[ ID = \int ds \int W(s) \]  

(3)

This equation has been showed to be widely applicable to many different varying steering tasks that correspond to parametric variations in the path width and length. For the simplistic case of a linear path with fixed width the ID can be represented as, \( ID = \frac{1}{W} \). Likewise, for the circular task this reduces to , \( ID = \frac{2\pi}{W} \) [26], [27], [29].

These Laws of Action have readily been applied to evaluate haptic device performance for various testbeds in pointing, crossing, and steering tasks [30]–[33]. The unique nature of the Haplet being easily attached to a tablet or mobile device provide the ability to produce collocated visuo-haptic displays which more closely replicate the nature of our physical interactions with our surroundings when performing dexterous manipulation tasks with our hands. Thus we aimed to test the ability of users to perform common performance evaluation tasks with a collocated visual display to see if it provided a marked performance improvement despite obstructing the view.

Two target sizes and task lengths were chosen for the three tasks ([\( A_{\text{min}} = 0.008m; A_{\text{max}} = 0.012m \)] and \([ W_{\text{min}} = 0.03m; W_{\text{max}} = 0.06m \)]). Users were presented the task on screen with a 1:1 isotonic mapping between the physical workspace and the virtual workspace. Overall, twenty-two users were selected to participate in the study ranging in age from 21 to 50 years old. The mean age of participants was 28 years old with 73% being male. The twelve total tasks were presented in a random order to reduce bias from adapting to the device. The participants were explicitly then asked to perform the presented tasks as quickly and accurately as possible. The hand the test subjects used for the test was not always their dominant hand though it was held constant throughout the trial. Users were allotted one practice run through the twelve total tasks for both the collocated and noncollocated testbed configurations. The task times were automatically recorded based on stopping and starting criteria that they originate on the starting points with zero velocity and end on the finish points with zero velocity. Errors resulting from missing the target locations or moving outside the specified channel widths were documented and excluded from the results.

The Indices of Performance saw a marked improvement in each of the three various testbeds as can be seen in Fig. 4. Beyond simple improvements in performance the collocated device and visual display saw a drastic reduction in the resulting errors for tasks with higher difficulty. The tasks that saw the most errors were both steering tasks with reduced target width. The net errors throughout all trials was reduced by 26.5% when the device was collocated with the visual display. Additionally, 82% of the participants reported that they preferred the collocated display and, despite their preference, each of the four participants that reported preferring the noncollocated display showed improved performance while operating in the collocated setup. The corresponding p-Values are listed in table I and indicate that the likely-
Fig. 4. Collocation effect on different tasks.

Fig. 5. Different device end-effectors were mounted for the two experiments. In the performance evaluation testbed a small passive revolute handle was mounted at the operation point (seen on the right). The texture-rating and discrimination experiments used a Planar Haptuator (Tactile Labs) (seen on the left) at the operation point for vibrotactile feedback generation.

Haplet’s end-effector shown on the left of Fig. 5, with a strap for the finger, is used to allow for three rendering modes (1: force only, 2: tactile only, 3: both). The Planar Haptuator (Tactile Labs) was employed for vibrotactile actuation. Along with the three material textures, these three rendering modes lead to 9 permutations.

In the first experiment, we played the 9 permutations in a random order. The participants were told what material is being rendered at each iteration, and they were asked to rate it on a 1-5 scale. The reference for comparison was three patches of real material textures made available to the participants in the beginning and throughout the entire experiment. The participants were instructed to move the Haplet’s end-effector constantly at an almost constant speed and not press down too hard. They were able to compare it with their feeling from moving their finger with the same speed and a firm pressure on the real material patch. The results are shown in Fig. 6.

In the second experiment, another random sequence of the 9 permutations was played. This time the participants were not told what they were supposed to feel at each iteration. Instead, they were asked to guess what material was rendered and they rated their confidence in their guess on a 1-3 scale. The confidence scale was defined to them as: 1) not confident at all, i.e. completely random guess; 2) some idea, e.g. almost equally hesitant between two choices; and, 3) fairly confident, i.e. maybe hesitating between two but leaning toward one. Each time they made a choice, without displaying it, their texture discrimination success (TDS) was computed as:

\[ TDS(mat, mode, part) = w \times m + (1 - w) \frac{1}{2}(c - 1) \]  

where \( c = 1, 2 \) or 3 is their confidence level; \( m = 1 \) or 0 is their match or no match success; and, \( w \in [0, 1] \) is the factor weighing the importance of the discrimination match versus confidence, chosen as 0.6 in this paper. Fig. 7 compares the mean of the TDS over the 19 participants for different rendering modes and materials.

### Table I

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<th>Tapping</th>
<th>Line Steering</th>
<th>Circular Steering</th>
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<tbody>
<tr>
<td>p-Value</td>
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<td>0.0062</td>
<td>0.0082</td>
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The p-values indicate strong support for the alternative hypothesis that collocation plays a significant role in improving user performance.
C. Discussion

The user performance results are somewhat intuitive and are consistent with previous results [35]: A user will perform a pointing or steering task better when they are given both visual feedback of the task and proprioceptive movement of the hand. Our objective was to discern this difference specifically for the tablet/laptop mounted use case of the Haplet. While users performed better with the collocated display, some reported that their hands obstructed their view of the tasks and negatively impacted their user experience. This, however, was rarely enough to impact their location preference. Also of note was the effect of slight mismatches in the calibration position leading to deviations of the endpoint. This had a large impact on the collocated tests but not on the noncollocated tasks as in the collocated setup they relied on the visual feedback of their hands and physical device exactly mapping to the virtually depicted device avatar. For noncollocated tasks users relied entirely on the virtual mapping between the device avatar and the obstacles.

When continuously probed and scratched by a rigid tool, a surface reveals a rich vibrotactile content. This content can be efficiently recreated with a localized vibrotactile actuator that emits a wide range of frequencies into a stylus-style gripper. This is exactly what has been done by Culbertson et al. [34]. In comparison with this tool-mediated touch, however, simulating direct touch is much more complicated and less investigated. Detecting high-bandwidth vibrations is not the main mechanism used in discrimination of textures by a finger. The soft nature of the finger tissues sacrifices reception of rich vibration content from a single contact-point, in favor for data collection and fusion by a distributed network of sensors. This network owes its efficacy to the skin deformation and its adaptability to the surface features. A simple Haptuator cell placed under a finger is not capable of mimicking such a distributed phenomenon; thus, is not expected to be very effective in simulating direct touch.

Despite this limitation, our initial experimental results show that the collocation of the Haptuator on the end-effector of the Haplet improves the results. Surprisingly, it actually outperforms the force feedback modality and sometimes even the integrated force-tactile mode. In analyzing figures 6 and 7, we should point out that the nature of the texture plays a key role in determining the importance of force versus tactile feedback. For discrimination of the whiteboard and silk textures, force feedback seems to be the preferred modality; while for textured metal, the vibrotactile modality was found to be more effective. The reason for the overall less effective performance of force feedback compared to tactile feedback in Fig. 6 can be sought in the simple friction model used for force rendering and some non-idealities in the Haplet transparency. Some participants reported the feeling from the Haplet’s inertia and backlash to interfere with texture perception. This explains why the vibrotactile feedback outperforms even the integrated force-tactile mode in Fig. 6. Future research can involve a better characterization of the Haplet properties and other improvements such as modifying the gear drive.

IV. CONCLUSIONS & FUTURE WORK

In an attempt to break through the limitations that exist in most available haptic platforms, we have created the Haplet: an open-source, portable and affordable haptic device with collocated visual, force and tactile feedback. The triple collocated user experience is delivered by a small-form parallel robotic arm that feature a simple vibrotactile actuator at the end-effector. The robotic arm is optically transparent and is motorized at the base where it clips on a tablet or computer screen. All the electronic components are encapsulated in a custom designed open-source board based on the Arduino Due microcontroller.

Effects of visuo-haptic collocation and force-tactile feedback integration were studied by means of experiments. The proposed triple-collocated Haplet design was found to deliver acceptable performance even for tasks as complex as texture discrimination. In fact, the Haplet is one of the few, if any, affordable means to facilitate research on complex topics such as direct haptic rendering of textures. This is the main motivation behind developing this platform. We believe that putting these technologies into the hands of a broader community will naturally lead to a faster collective effort toward finding better solutions for simulating direct touch and other challenges in haptics.

Examples of future work include using the Haplet board for developing higher DoF devices and VR applications. Another important topic of interest is conducting case studies with Haplet platforms in classroom and educational settings.

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