Transcalibur: A Weight Shifting Virtual Reality Controller for 2D Shape Rendering based on Computational Perception Model

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Figure 1: Transcalibur can dynamically present size of various object in VR, actuating weight and angle mechanisms. Although the actual contoroller's appearance differs from its appearance in VR, a user feels as if s/he is wielding a sword (left), a gun (center) and a crossbow (right) with the same VR controller.

ABSTRACT

Humans can estimate the shape of a wielded object through the illusory feeling of the mass properties of the object obtained using their hands. Even though the shape of hand-held objects influences immersion and realism in virtual reality (VR), it is difficult to design VR controllers for rendering desired shapes according to the perceptions derived from the illusory effects of mass properties and shape perception. We propose Transcalibur, which is a hand-held VR controller that can render a 2D shape by changing its mass properties on a 2D planar area. We built a computational perception model using a data-driven approach from the collected data pairs of mass properties and perceived shapes. This enables Transcalibur to easily and effectively provide convincing shape perception based on complex illusory effects. Our user study showed that the system succeeded in providing the perception of various desired shapes in a virtual environment.

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CCS CONCEPTS

• **Human-centered computing** → **Haptic devices**; • **Computing methodologies** → *Virtual reality*; *Perception.*

KEYWORDS

Computational interaction; Haptic display; Virtual reality; Shape perception

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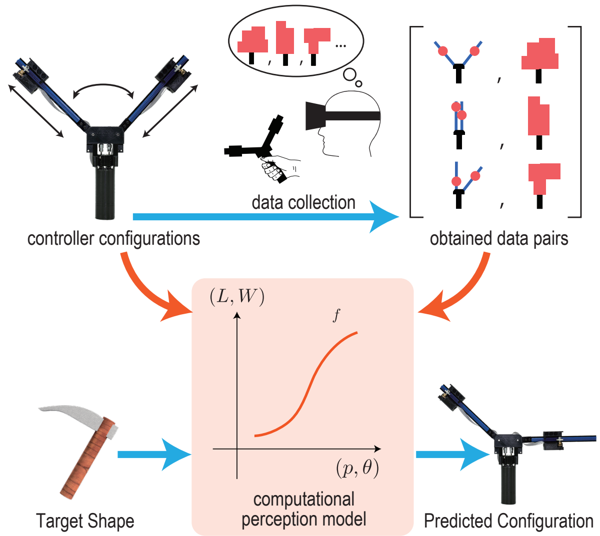

Figure 2: Transcalibur renders shape using the computational perception model obtained by data collection. The collected data is fit to the regression model, which predicts the optimal configuration of the controller for the target shape in VR.

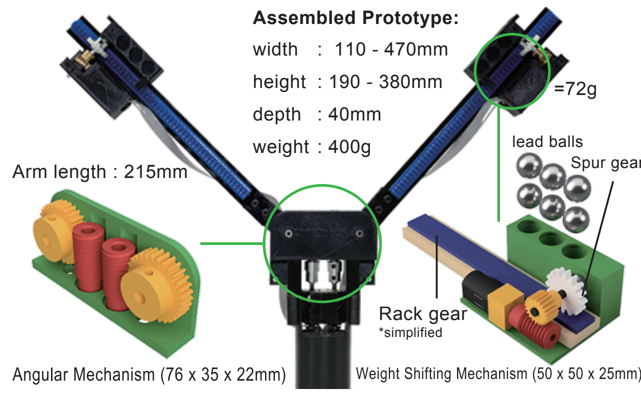

Figure 3: Mechanical design of the proposed device. The angular mechanism (left bottom) and weight shifting mechanism (right bottom) are actuated by a motor through the worm (red) and the worm wheel (yellow).

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1 INTRODUCTION

Intensive developments in computing power and the increasing resolution of displays have enabled virtual reality (VR) to become accessible for everyone and at any location. With the growing demand for rich immersion and realism in VR along high audiovisual fidelity, there is a significant need for haptic feedback techniques since interaction between virtual object and users is essential for VR. Thus, the number of haptic devices for VR has been proposed that are mainly focused on providing force [2, 3, 11, 16, 21] or texture or tactile feedback [29]. As for immersion, the sensation of the shape of the wielded object in VR is also important. Because conventional VR controllers cannot render the shape of virtual objects, they thus lack immersion and realism.

Several haptic displays for shape have been proposed based on human shape perception mechanism: understanding the shape of hand-held object *without even seeing it*. A weight shifting mechanism for a variable length [31] can alter the wielding sensation of a 1D object. Fabricating props that matches perceived shape in VR [5] will generate an optimized shape for size and haptic equivalence. However, these haptic displays are limited in variety of rendered shapes and cannot be applied to different objects or contexts for an interactive VR experience.

We propose a weight shifting controller for dynamic 2D haptic shape rendering. The resulting device: *Transcalibur* has a weight shifting mechanism and angle mechanism that alters mass properties in a 2D planar area, which allows for rendering various shape sensation.

Although psychological studies have revealed how the mass properties or inertia of the wielded object affect the perceived shape of an unseen object, deterministic mapping between the mass property and the perceived shape cannot be derived owing to the nonlinearity of human perception characteristics. This makes it difficult to manually adjust and configure Transcalibur's weight positions. In this paper, we also applied a data-driven method to determine the best physical state of Transcalibur for the desired object to render in VR: namely the Computational Perception Model.

Figure 2 shows our approach. Based on the object shown in VR, the shape of the controller that users grasp is dynamically changed so that its shape perception matches the target object. In our system, we create a computational model that maps mass properties to haptically perceived shape using a data-driven approach. We correct the perceived shape data of the VR controller with different mass properties through a perceptual experiment and map these data using regression. From the model, we determine the mass properties of the VR controller that optimizes the perceived shape of the controller to be the target object shown in virtual environment (VE). In this manner, we can easily and efficiently render an arbitrary 2D shape through the controller.

2 TRANSCALIBUR

Transcalibur is a hand-held VR controller that dynamically and illusorily changes the perceived shape of a 2D object. Figure 3 shows the hardware overview of the Transcalibur.

The weight moving mechanisms on the controller changes its 2D mass properties, which provides various shape perceptions for the user in VR. The perceived shape can be rendered based on a perception model which is built by precollected perception data through our experiment. In this section, we describe the core concept of Transcalibur.

Computational Perception Model on Haptic Shape Illusion

When we grab and wiggle an object, we feel the object through haptic sensation: the skin on the hand in contact will be stretched and the muscles and tendons of the arm will contract. This means that humans can guess what s/he is holding even when their *eyes are closed*. Researchers in psychology have revealed that the mass properties of an object, such as rotational inertia and center of gravity, affect the perception of what shape of the object people are wielding [13, 19, 26, 27]. This occurs even when the actual shape differs from the perceived shape. That being said, we can *illusorily* present various sensations of wielded objects through changes in the mass properties of the object. We call this *Haptic Shape Illusion*. By utilizing this effect, we can *simulate* the shape of a wielded object without using the actual shape of a targeted object.

This will allow the system to reduce the spatial cost when provided with a large object such as a longsword or an axe in the game as it is important to provide various haptic sensations at a low cost in conventional VR systems for the public. Our approach is to simulate haptic feedback through the illusion. Transcalibur aims to provide such an effect dynamically using just a single controller.

Haptic shape illusion involves utilizing the perceptual illusion existing between the mass properties of a wielding object and shape perception. However, in most cases, this relation makes it difficult to predict how or how much of the illusion effect could occur, especially for a VR experience designer, owing to the nonlinearity of human perception, which means that what one perceives is not always consistent with what one is actually exposed to. Even if the type of sensory input and perceptual phenomenon are clarified through previous psychology studies, their mapping must be restudied and reoptimized when a device or an environment that we assume is different from the one observed in previous studies. Even though this procedure is necessary for constructing this type of interface, finding the mapping through psychophysics studies that repeatedly presents different sensory stimuli to determine the occurrence of the perceptual phenomenon requires considerable time and effort.

To overcome this problem, we apply the *Computational Perception Model* to this device. This approach allows providing haptic feedback based on actual human perception data. We collect data pairs of physical configurations of Transcalibur (positions of weight modules on the controller) and the shapes displayed in VR for users and fit to the machine learning model. Then, from the desired shape that we want to display in VR, we derive Transcalibur configurations from the trained model. In this manner, we can easily and efficiently design and provide haptic shape experiences for various users.

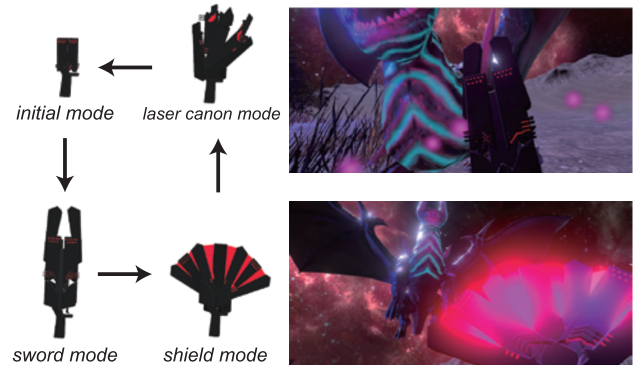

Figure 4: Application footage from the exhibition venue. The left image shows the transition between different weapons in VE. The right image shows the game footage of players fighting the dragon with a sword (above) and blocking dragon breath with a shield (below).

Application

Transcalibur can be used in VR gaming experience. We implemented a VR game wherein users can fight against a dragon using various weapons. We demonstrated the application at an international HCI conference. We also conducted an absolute qualitative questionnaire after a 3-min demo. In this demonstration, users can wield, attack, defend themselves against fireballs, and shoot the dragon in a virtual environment that provides users with various sensations of the wielded object (Figure 4). We asked 197 visitors whether the system helped the users feel various shapes and how immersive was the experience with 7-point Likert scale. The participants answered that the device made them feel *change in width* (6.0) and *height* (5.8), and the device helped them feel *immerse* (6.2) and *realistic* (6.0) in VR. The users commented on the system as *"totally immersive"* and *"definitely felt the change"* for the shape of the objects in VR.

Transcalibur can also be applied to other types of VR situation, such as presenting shape or weight in VR training in a factory, disaster site or surgical operation. It is expected to improve realism and training effect in such VR experiences.

3 CONTRIBUTION

Our main contribution is a novel haptic-rendering VR controller that can dynamically render shape of a virtual object over a wide range by exploiting size perception of a wielded object. This concept is known as *dynamic touch* [26]. This allowed users to feel as if they are holding the various objects displayed in VR in a more immersive manner.

The key idea of the data-driven approach is to overcome the fact that there is no analytical mapping between the physical property of the controller and user perception. Shape rendering across users is accomplished by sampling the users' perception, and by providing optimal configuration based on collected samples. We validated its effectiveness through the experiment, and demonstrated that the device could render shapes across a wide range.

4 RELATED WORK

Transcalibur is inspired by various related studies from the field of haptic feedback in a virtual environment. Our idea of a shape-changing controller is also based on previous studies on shape perception of a wielded object and its applications for VR.

Haptic Display for VR

There are numerous projects that deal with increasing immersion and realism in VR by providing various types of haptic feedback. A force feedback system with mechanical linkages is used to simulate contact against a human body. Linkages on the hand [3, 6, 30] or fingers [2, 22] are used to simulate grasping virtual objects. Collisions on the fingers are simulated as well [22, 29]. Actuators are attached to a conventional VR controller to combine tracking and button input capability with a force feedback system [25]. These force feedback systems require a number of actuators, especially for 6-DoF force feedback, that have to be grounded, and this makes the mechanism more complicated and expensive. Propeller for aerobotics or drones are applied [8, 11, 21] to provide force feedback as well, but they emit considerable noise and wind while being used, which is distracting for an immersive VR experience.

Electrical muscle stimulation (EMS) is applied to simulate various haptic sensation without any mechanical components [14, 15]. As it has been demonstrated that EMS can present sensation of impact [14] or weight of the object in one's hands [15], it is expected to enhance our system when combined with EMS.

Vibrotactile feedback is used to simulate texture or vibration. This method is widely used for its small implementation cost, and varieties of interaction designs in immersive experience that convey information to users are proposed, such as motion effects [18] or navigation [23]. Currently, most conventional VR controllers have vibration motors implemented for haptic feedback. Vibrotactile actuators are also used to render weight perception using an asymmetric vibration technique [12, 16, 20], and these type of forces can also be combined with Transcalibur, by applying vibration at the handle.

The weight shifting mechanisms for tangible interfaces and haptic feedback using liquid metal [17], audio fader [7] and servo controlled robotic arm [28] are proposed. Transcalibur's mechanisms shown in Figure 3 are particularly designed to endure a certain amount of acceleration or force induced by users shaking the controller.

As stated above, various haptic techniques are developed for VR applications. On the contrary, 2D dynamic shape rendering in a virtual environment is not well st udied, and there are increasing examples that users can wield various objects in VR, such as a sword, bow, or wands in action games, brushes or sculpture tools in VR paint. As light-weighted conventional VR controllers lacks the ability to render weight or shape sensation, there is a demand for such capability in a VR controller as we aimed for. Simultaneously, implementing heavy and complex mechanisms in a VR controller is problematic as it might lead to issues with scalability. Hence, in this project, we also aimed at utilizing human perception of the shape of the wielded object from the perspective of *illusion*.

Shape perception, Displays, and Applications for VR

Researchers in the psychological field explored the underlying mechanisms of the ability of estimating size and shapes of the wielded object. "Dynamic Touch" named by Turvey et al. [26] has been investigated through various psychological experiments [19, 24, 27]. Based on these results, it has been observed that the principal component of the objectâĂŹs inertia tensor plays a significant role in perceiving shape.

Several haptic displays for shape perception have been proposed. As for a Tabletop-type, shape displays using a 2D array of linear actuators are proposed [4, 9, 10] to render the geometric surface of the virtual object. shapeShift enables to track and freely move the array shape display and renders the shape of a spatially registered object. Zhao et al. [32] proposed a self-assembling multi-robot system to present a physical equivalent of the target object. However, these types of devices require several motors and mechanical components. Benko et.al. [1] utilized a displacement on a fingertip to render the shape of a virtual object in VR. However, these types of devices require several motors and mechanical components.

Shifty [31] is a VR controller that simulates the length of the object by moving the weight on the stick, and the motion is tracked by a VR system so that the users can feel its change along the length in VR. This device also enables thickness rendering, but the variety of the shape rendered by this device is constrained in a 1D symmetric shape.

Fujinawa et al. [5] proposed a system to generate computationally optimized laser-cut props to provide the haptic equivalent shape of the target object. The laser-cut objects are generated in a manner that the mass property of the perceived object to the subjective perception of shape matches, and such objects are generated by pre-collected data through the experiment. The system will optimize and generate the props to reduce its shape compared to the target shape so that there will be less danger of hitting environment or properties by large props. As the system will generate a laser-cut object and it is mapped to a single *static* object, the provided haptic sensation is limited.

Transcalibur is inspired by these projects and our goal is to make the haptic feedback *dynamic*. Our system implements the mechanism to dynamically change its mass property and provides shape perception of a target object generated by collected data. In this manner, the system can provide various shapes for a virtual object with just a single controller, which will help users with being more immersed in VR.

5 HARDWARE IMPLEMENTATION

The overall hardware specifications are shown in Figure 3. The weight moving mechanism is designed to move along the 2D planner space and to be *non-backdrivable*. In this section, we present the mechanical design and setup of Transcalibur to help readers replicate the device.

Angular Mechanism

The angular mechanism enables to rotate two arms independently. Two arms are made of 5mm acrylic laser-cut plate and plastic rack gears are attached to each of the arms. A worm wheel is placed at the bottom of each arm, and a worm connected to the worm wheel is actuated by a Pololu 150:1 HPCB 12V Micro Metal Gearmotor with a magnetic encoder. The cover of these gears and motors were 3D-printed with PLA material, and the casing is made for wireless VIVE Tracker be attached so that the controller can both be tracked and communicated. The angular mechanism has a *non-back-drivable* design owing to the worm and the wrom wheel so that these arms can maintain their angle even if some torque were applied to the angular mechanism by shaking the device. The setup of our prototype is capable of moving each arm 90 degrees in approximately 2 s.

Weight Shifting Mechanism

Transcalibur has two rectangular-shaped modules that shift weight positions, which are called *weight modules*. Each modules also includes a worm and a worm wheel. A spur gear is connected to the worm wheel through a metal shaft then to a rack gear, and the rack gear is attached to the arm. Coil springs are applied to the shaft to adjust the mesh between the spur gear and the rack gear. A Pololu 50:1 HPCB 12 V Micro Metal Gearmotor with a magnetic encoder is placed in a PLA casing with the gears. The motor is connected to the worm, and the PLA casing itself moves on the arm by actuating the motor. The PLA casing has three cylindrical space to store small lead balls to adjust the weight of the module. The weight of one module, including the gears, motor, 6 lead balls, and PLA case, is 72 grams. The weight module also has a *non-back-drivable* design so that the weight modules can maintain their positions on the arms even if some torque were applied to the angular mechanism by shaking the device. The weight module is capable of moving 100 mm in approximately 4 s.

Electronics and Communication

Transcalibur is controlled by Teensy 3.2 with ARM 72MHz Cortex-M4 MCU, programmed by Arduino IDE. Each motor in each mechanism is driven by DRV8871 motor drivers and is connected to the MCU. The device is powered by DC voltage of 12 V, and a regulated voltage of 5 V is supplied both to the MCU and the motor drivers. MCU and motor drivers are mounted on printed circuit board (PCB) and stowed in 3D printed PLA handle of Transcalibur. Position data can be transferred by both USB-serial communication and electric signals that can be obtained from Pogo pins connected to the HTC VIVE Tracker. The position or angle of mechanisms is monitored and controlled by magnetic encoders attached to the motors of each mechanism.

6 PERCEPTION MODEL DESIGN

For computational derivation of shape of the hand-held controller for desired shape feedback, we conducted data collection using our prototype. Then, the collected data pairs are fitted as a linear regression model that provides the predicted shapes that matches the target object in VR. In this section, we explain how we build a perception model that maps the physical state of Transcalibur to the users' shape perception in VR.

Mapping from Controller to Virtual Shape

As a previous work on computational fabrication of hand-held controller [5] proposed, we assumed a perception model f that maps the physical configuration of the controller ϕ to the perceived shape of the wielded object in VR ψ:

$$f : \phi \mapsto \psi \tag{1}$$

Transcalibur has four configuration parameters: positions of the weight module on the arms, and angles of the angular mechanism of the arms. In this manner, Transcalibur can change its inertia moment and center of gravity, then alter shape perception of an hand held object. Since we want to give a perceived object mapped to a mechanical configuration of Transcalibur instead of directly calculating inertia tensor, we represent this as $\phi = (p_\mathrm{r}, \theta_\mathrm{r}, p_\mathrm{l}, \theta_\mathrm{l})$ and ϕ_i as i-th obtained through the data collection experiment.

On the contrary, we represent the perceived object using its 2D boundary box of the object and its center of gravity (CoG) as $\psi = (H, W, G_x, G_y)$, where an obtained i-th data is written ψ_i as well. Our goal is to provide the best estimate of the shape of the controller ϕ from the model f, given the target perceived object ψ in VR. We describe the manner in which we collected data, built the model, and estimated the values.

Collecting Perceived Shape Data

Experiment Set. In the data collection experiment, we provided the participants with various shapes of the controller and asked them to report the perceived shapes in VE. This generates matched pairs of (ϕ_i, ψ_i), which are used to build a regression model for the training data. To collect various shapes over a wide range within the constraints of the user study, we manually defined the number of shapes to provide in VE. The mass properties of the controller presented and the exact values used for configurations are shown in Figure 5. Because we consider those shapes that will remain the same when the controller is flipped, $49 - (49 - 7)/2 = 28$ different configurations of the controller are presented to the participants.

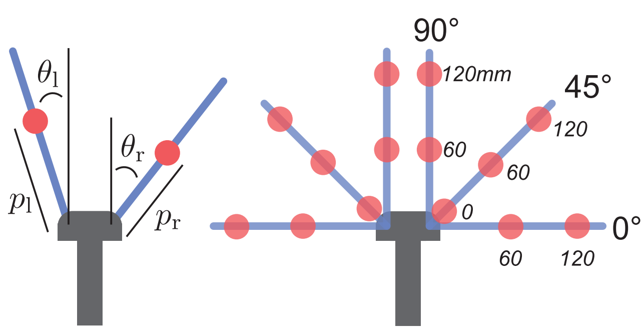

Figure 5: Illustrated configuration variables of Transcalibur $(p_\mathrm{r}, \theta_\mathrm{r}, p_\mathrm{l}, \theta_\mathrm{l})$. The red circles illustrate the positions of the weight module (left). Group of variables used in the experiment (right).

VR System. In the data collection experiment, participants wore a HTC Vive head-mounted display (HMD) that was tracked by its motion capture cameras (VIVE lightroom). The VE is run on Unity game engine, and deployed using a gaming PC (iiyama LEVEL infinity, Intel Core i7-6700 CPU @ 3.40 GHz, NVIDIA GeForce GTX 1080), and a joypad (Sony Playstation DUALSHOCK4) is utilized for user input. A Vive tracker is attached to Transcalibur for motion tracking and wireless communication. In the VE, participants can see a virtual handle in the exact same size and position as the actual Transcalibur and can move/operate it naturally. On the top of the handle, four red rectangular plates are mounted, and users can adjust their heights and widths using the joypad. Figure 6 shows the eight parameters or adjustable shapes in the VE, and we describe these as an input:

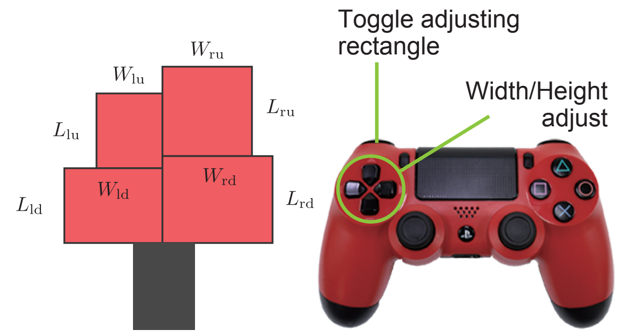

Figure 6: Presented shape in VE and its eight parameters (left), and joypad configuration used in the experiment (right). Each of the four rectangles on the top of the handle can be adjusted using the joypad until users feel its match to the perceived shape through the controller. Coordinate axis for CoG is defined in this figure.

$$d_i = (H_\mathrm{ru}, W_\mathrm{ru}, H_\mathrm{rd}, W_\mathrm{rd}, H_\mathrm{lu}, W_\mathrm{lu}, H_\mathrm{ld}, W_\mathrm{ld})_i \qquad (2)$$

These eight variables are converted into four variables representing a rectangular bounding box the shape and a Center of Gravity (CoG) coordinates (H, W, G_x, G_y). As described in the section "Mapping from Controller to Virtual Shape", this description makes simpler to represent the mass property of the perceived object, and easier for mathematical model to fit the training data. Participants were then asked to adjust these eight variables with the trigger button and arrow keys of the joypad such that the virtual appearance matched the haptically perceived shape. We also presented hardware having an acrylic square plane identical to the initial size of the VR object as a *reference controller* to control the assumptions for the material displayed in VR, which may otherwise differ among participants. We consider that the weights of the VIVE tracker, which is attached to Transcalibur, and acrylic square plane controller affect the perception of the shape; therefore, the 3D model of the VIVE tracker is also visually presented in VR (Figure 7).

Procedure. Participants were asked to sit on a chair, wear a HMD, hold the joypad with their non-dominant hand, and hold Transcalibur with their dominant hand. We then selected one of the prepared configurations of the controller,

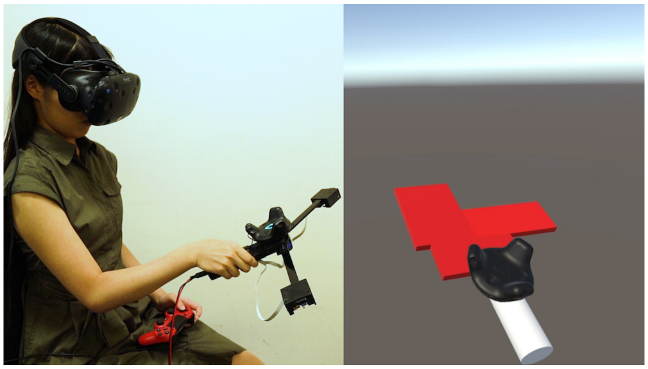

Figure 7: In the data collection experiment, a participant grabs and wiggles the Transcalibur with him/her dominant hand and uses joypad with him/her non dominant hand. In VE (right) the participants can see the adjustable shape.

and displayed the adjustable virtual shape in VR. The virtual shape had two *initial shapes* that controlled initial assumptions: The first was a 100 mm × 100 mm square, and the other was a 600 mm × 600 mm square shape.

At the start of each trial, participants wielded the reference controller. Participants then estimated the shape of the controller by wielding it and wiggling it to various directions, and adjusted the shape of virtual shape using the joypad. Once the calibration is complete, participants put Transcalibur on the desk and we record the eight variables of the controller, marking the end of a trial.

For each prepared configuration, each one of configurations is performed twice as we presented two *initial shapes*, and a total of $28 \times 2 = 56$ trials were presented in random order to each participant. Participants were allowed a 2 min break once every 14 trials. In this experiment, six participants were involved including one left-handed person, and their ages varied from 20 to 23. As a reward for participation, we provided 10$ amazon coupons to each participant.

Data Aggregation. Through the data collection, we obtained a total of $56 \times 6 = 336$ data pairs (ϕ_i, ψ_i). Each input data d_i was then converted into four variables (ψ_i) by calculating the rectangular bounding box of the input shape, and CoG coordinates. We also added *mirrored* shapes as training data: variables that were symmetric in shape. For example, if a data pair (ϕ_i, ψ_i) is $\{(0, 120, 60, 90), (20, 40, 10, 20)\}$, we also added $(\phi_k, \psi_k) = \{(60, 90, 0, 120), (20, 40, -10, 20)\}$ as valid training data. In this manner, we finally obtained $49 \times 2 \times 6 = 588$ data pairs for training the model.

Regression Models and Results

Using the obtained data pairs, we performed regression analysis to build a map f from the configurations of the controller onto the perceived shapes. For each parameter in ϕ, we used a linear regression model and trained model $\psi = f(\phi; \boldsymbol{A}, \boldsymbol{b})$ to describe the perceived shape $\psi = \phi\boldsymbol{A} + \boldsymbol{b}$, where $\boldsymbol{A} \in \boldsymbol{R}^{4\times4}, \boldsymbol{b} \in \boldsymbol{R}^{1\times4}$ as parameter and $\phi, \psi \in \boldsymbol{R}^{1\times4}$ as an input and output data. The other regression models were compared in terms of prediction errors, and we decided to use the linear regression model because the errors did not differ significantly among different models (Table 1).

Table 1: Prediction errors of different regression models. LR = linear regression, QR = quadraic regression, TR = tertiary regression.

	LR	QR	TR
Error in H [mm]	108.1	102.3	100.1
Error in W [mm]	265.7	247.5	243.2
Error in G_x [mm]	28.8	24.6	23.0
Error in G_y [mm]	32.5	31.0	30.4

Configuration Prediction for Target Shape in VR

Using the model built from the collected data, we aimed to derive the best shape of Transcalibur as the perceived shape in VR that is closest to the target shape S^{target}. We define a cost value E as the squared distance between the perceived and target shapes, and we choose the physical configuration of Transcalibur that minimizes the cost value. The regressed values of height, width, and CoG coordinates can be computed from the shape perception model f, and the cost value is defined as the sum of the error factors for each of the virtual shape properties:

$$E = E_{\mathrm{H}} + E_{\mathrm{W}} + E_{\mathrm{G}_x} + E_{\mathrm{G}_y} \tag{3}$$

where each cost can be described using the perceived height H, width W and CoG (G_x, G_y) and the target height H^{target}, width W^{target}, and CoG $(\mathrm{G}_x{}^{\text{target}}, \mathrm{G}_y{}^{\text{target}})$.

$$E_{\mathrm{H}} = ||f_{\mathrm{H}}(p_{\mathrm{r}}, \theta_{\mathrm{r}}, p_{\mathrm{l}}, \theta_{\mathrm{l}}) - H^{\text{target}}||^2 \tag{4}$$

$$E_{\mathrm{W}} = ||f_{\mathrm{W}}(p_{\mathrm{r}}, \theta_{\mathrm{r}}, p_{\mathrm{l}}, \theta_{\mathrm{l}}) - W^{\text{target}}||^2 \tag{5}$$

$$E_{\mathrm{G}_x} = ||f_{\mathrm{G}_x}(p_{\mathrm{r}}, \theta_{\mathrm{r}}, p_{\mathrm{l}}, \theta_{\mathrm{l}}) - \mathrm{G}_x{}^{\text{target}}||^2 \tag{6}$$

$$E_{\mathrm{G}_y} = ||f_{\mathrm{G}_y}(p_{\mathrm{r}}, \theta_{\mathrm{r}}, p_{\mathrm{l}}, \theta_{\mathrm{l}}) - \mathrm{G}_y{}^{\text{target}}||^2 \tag{7}$$

To obtain an optimal controller shape ϕ^*, we defined the following optimization problem with the hardware constraints of the controller.

$$\begin{cases} \phi^* = \underset{\phi}{\arg\min}\ E \\ s.t. \quad 0 \le p_{\mathrm{r}}, p_{\mathrm{l}} \le 125, 0 \le \theta_{\mathrm{r}}, \theta_{\mathrm{l}} \le 90 \end{cases} \tag{8}$$

We used COBYLA optimizer for solving the linear regression prediction and executed the solution in the Python Scikit-learn environment. Figure 9 shows examples of the predicted shapes of the controller calculated by the optimizer, which are later used in the evaluation experiments. Figure 8

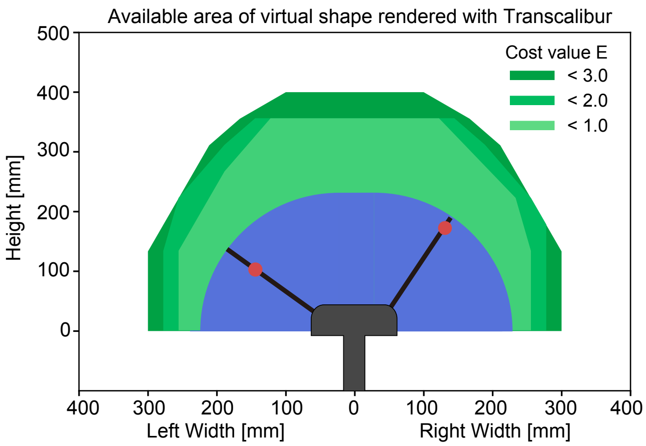

Figure 8: Area of the shape that Transcalibur can render in VE (green), and the physical boundary of Transcalibur (blue). The shape within the green area has a predication error value of $E < E_{\text{Threshold}} = \{1.0, 2.0, 3.0\}$.

Table 2: Properties of the ten virtual shapes (illustrated in Figure 9) and their corresponding predicted configurations for Transcalibur (units are mm and degree).

id	H	W	G_x	G_y	p_r	p_l	θ_r	θ_l
1	325	150	0	162.5	103	93	90	90
2	150	400	0	75	106	125	12	18
3	275	275	0	137.5	125	125	65	65
4	200	200	0	100	0	9	51	47
5	250	250	0	89	75	77	56	59
6	250	250	0	161	125	125	68	68
7	125	350	-75	62.5	0	125	0	23
8	250	250	75	125	125	0	46	90
9	250	250	28.8	102	88	95	15	90
10	250	250	-28.8	148	78	125	82	52

shows the relative area (height and width) of the predicted shape that Transcalibur can render when the prediction result is less than the cost value $E < E_{\text{Threshold}} = \{1.0, 2.0, 3.0\}$. A slight asymmetricity is obsereved in the calculated covering area since we did not assume symmetricity in the perception model. The covering area also is larger than the physical size of the Transcalibur, which means that our shape rendering technique is also able to exceed the physical bound of the controller.

7 MODEL EVALUATION

To measure the validity of the perception model, we conducted validation experiments. We prepared ten shapes to present in the VE, which can be described using the same parameter format d_i as that of the data collection experiment (Figure 9 and Table2). The ten virtual shapes were manually determined such that variations in height, width, symmetricity, and asymmetricity of the target shapes could be evaluated.

Procedure

Participants were asked to hold Transcalibur while wearing the HMD, and we randomly presented ten prepared configurations to the controller. For each configuration, one of ten virtual shapes were presented and the tracked positions were displayed on the controller similar to the procedure in the data collection experiment. Participants could switch between the ten virtual shapes using the joypad, and they were asked to press a button to confirm that the shape in VE that best matched the perceived shape through the Transcalibur. The experiment hardware setup was prepared similar to that for data collection. In this experiment, 12 participants were enrolled including one left-handed person, and their ages ranged from 22 to 24.

Results and Discussion

Figure 10 shows the confusion matrix derived from the accuracies of the selected shapes of the object.

Overall, our perception model succeeded in providing various target shapes in VR for Transcalibur, leaving a few shapes with confusions on shapes 4 and 5 or 8 and 9.

Symmetric shapes such as 1, 2, and 3 were accurately classified. Rectangular shape 3 had a slight confusion with 5 and 6, which mainly differed in G_y. Asymmetric shapes such as 7, 8, 9, and 10 were also classified with reasonable accuracies, but produced some confusions between 8 and 9, which differed in both G_x and G_y.

These confusions might have been caused by the strong correlations between G_y and H, which is an observation that is supported by a previous study [13], and this caused difficulties in discriminating objects of similar height but different CoGs in the height direction. Further, extreme shapes such as 5 were not observed in the data collection session, where the wide component close to the grip looked like a sword but did not allow users any inputs during data collection.

Otherwise, most of the presented configurations were answered as the desired target shapes, and this suggests that our system succeeded in rendering various shapes of hand-held objects in VR.

8 LIMITATIONS

Hardware Constraints

First, the hardware mechanism does not allow displaying mass property along three-dimensional space. Since Shifty [31] showed that the 1D movement of weight can provide a thickness of the object, there is a possibility that our device could also render shapes in 3D, which may be achieved by

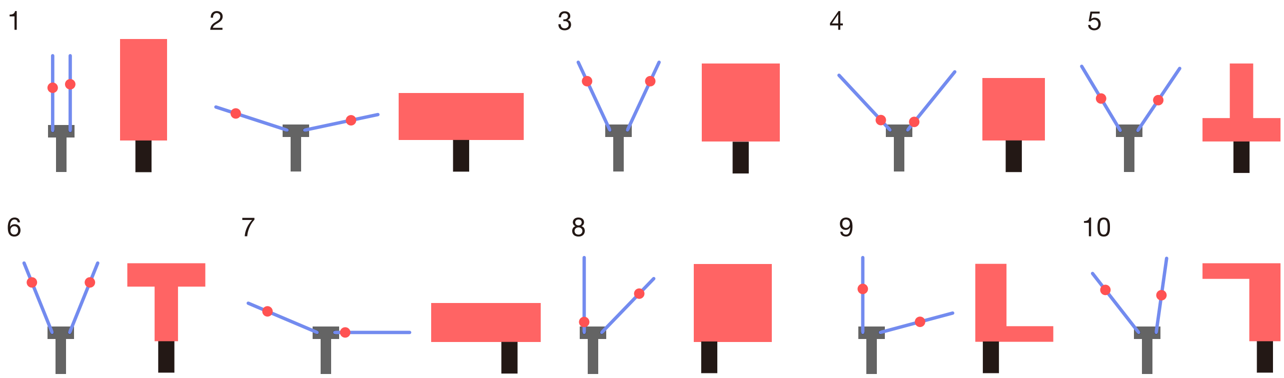

Figure 9: Ten pairs of physical properties of Transcalibur and their corresponding virtual shapes provided in the experiment. Each configuration of Transcalibur is predicted from the linear regression model.

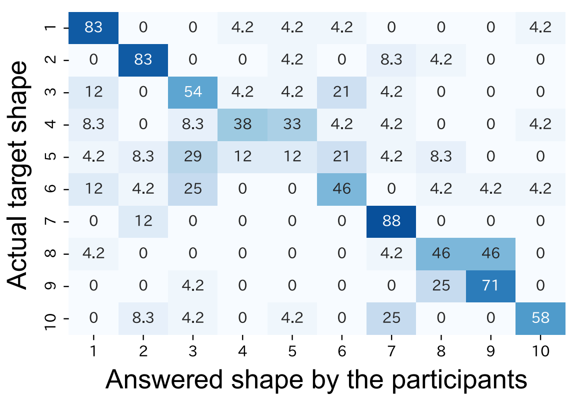

Figure 10: Confusion matrix derived from the results of the experiment. Each row shows ratio [%] of the actual target shape answered as the test shape in VR.

combining visual feedback. Second, our device must be actuated by DC motors. As most conventional VR controllers do not have actuators except vibration motors, there is still a difficulty to apply this method widely.

Our current device has been prototyped that we can explore whether shape perception with the data-driven approach can be achieved. For optimal design of weight shifting mechanism and safety, it is expected that we can utilize time for our perception model as we describe on next section: weight mechanism actuates as VR object transforms.

Rendering of Shape over Time and Order

Testimonies of our demo application also suggested that users could perceive changes in shapes strongly when Transcalibur changed its shape at the time the object in VE changed its shape. Although, our experiment did not include factors of change in shape over time, which is also closely relevant to *order effect* of human perception: the perception differs one after another and is not consistent over trials. If we exploit the dynamic motion based on perception model, it might widen the range of shape rendering then leads to optimize the device dimension for light-weight and safe design.

Special Physical Properties of Virtual Objects

Transcalibur is intended to render shape perception by altering mass properties. Other haptic effects caused by changes in shape such as air resistance felt by wiggling wide objects are neither included in the model nor simulated. The proposed data-driven method may include some design tradeoffs: we can efficiently design a wide range of haptic experiences of specific properties, but it is difficult to completely replicate side effects caused by the physical phenomena. This is mainly due to simplification of the data collection procedure and based on VR experience that the designer might need to include such factors in the perception model.

9 CONCLUSION

In this paper, we introduced Transcalibur: the weight moving VR controller for 2D haptic shape illusion. We implemented a hardware prototype, which can change its mass property in 2D planar space, and applied data-driven methods to obtain maps between mass property and perceived shape. Based on the demonstration and experiment, we succeeded in rendering various shape perceptions through the controller based on pre-computed perception model. As a future work, we further investigate details on time factor of shape changing in VR, and we aim to develop a simpler design and yet maximizes range of rendering shape.

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