# Haptic Around: Multiple Tactile Sensations for Immersive Environment and Interaction in Virtual Reality


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## ABSTRACT

In this paper, we present Haptic Around, a hybrid-haptic feedback system, which utilizes fan, hot air blower, mist creator and heat light to recreate multiple tactile sensations in virtual reality for enhancing the immersive environment and interaction. This system consists of a steerable haptic device rigged on the top of the user head and a handheld device also with haptics feedbacks to simultaneously provide tactile sensations to the users in a 2m x 2m space. The steerable haptic device can enhance the immersive environment for providing full body experience, such as heat in the desert or cold in the snow mountain. Additionally, the handheld device can enhance the immersive interaction for providing partial body experience, such as heating the iron or quenching the hot iron. With our system, the users can perceive visual, auditory and haptic when they are moving around in virtual space and interacting with virtual object. In our study, the result has shown the potential of the hybrid-haptic feedback system, which the participants rated the enjoyment, realism, quality, immersion higher than the other.


## CCS CONCEPTS

•Human-centered computing→Virtual reality; •Computing methodologies →Perception; Shape modeling;


## KEYWORDS

Haptics; Multiple Tactile Sensation; Virtual Reality; Immersive Environment; Immersive Experience.

**ACM Reference format:**

Ping-Hsuan Han, Yang-Sheng Chen, Kong-Chang Lee, Hao-Chang Wang, Chiao-En Hsieh, Jui-Chun Hsiao, Chien-Hsing Chou and Yi-Ping Hung. 2018. Haptic Around: Multiple Tactile Sensations for Immersive Environment and Interaction in Virtual Reality. In *Proceedings of ACM Symposium on Virtual Reality Software and Technology (VRST'18). ACM, Tokyo, Japan, 10 pages.* https://doi.org/10.1145/3281505.3281507



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*VRST '18*, November 28-December 1, 2018, Tokyo, Japan


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ACM ISBN 978-1-4503-6086-9/18/11…$15.00
https://doi.org/10.1145/3281505.3281507


**Figure 1: Combining ubiquitous-based haptics and controller-based haptics in the immersive VR.**

## 1 INTRODUCTION

With the advance of virtual reality head-mounted display (VR-HMD), many research groups have shown the potential of utilizing haptic techniques in VR. To enhance the immersive experience in the virtual reality (VR) system, adding multiple tactile sensations is one of the quick and useful methods for providing strong feedback to the user (Figure 1), which includes kinesthesia and cutaneous feedback. TurkDeck [1] have referred the differences between the walking experience and touching object experience. Manipulating object and moving around in the virtual space is the key to explore virtual world. With haptic technology and HMD, the users not only can perceive visual and auditory feedback but perceive related haptic when they are doing their exploration. However, the human somatosensory system is a complex system, which has various human receptors to be activated by the different stimuli. Currently, to recreate the tactile sensation in virtual reality is a challenge, there were no such a haptic display can simulate all stimuli to provide the diversity of tactile sensation. Most of works developed the novel haptic display base on one or few of the human perception (tactile sensation), such as vibration [2], temperature [3], pressure [4], friction [4], texture or shape [5]. Therefore, when someone want to develop an VR simulation/application with haptic feedback, it depends on what is this for and how immersive they want, which will make each simulation has their own specific purpose.

In this paper, we propose a hybrid-haptic feedback system based on the concept of three elements of life (sun, air and water) which utilize heat light, fan, hot air blower and mist creator to recreate multiple tactile sensations in virtual reality. The system consists of ubiquitous-based Haptics and controller-based haptics. With the system, the user can move around in virtual space and perceive the non-contact tactile sensations from the environment. Meanwhile, the user also can feel the sensation when they are manipulating the virtual object. The main contributions of this work are summarized as follows. First, we developed three immersive VR application with haptic feedbacks for exploratory observation study. Second, we provide the design considerations, system design and implementation details for the hybrid-haptic feedback system. Third, a user study is conduct for investigating the immersion of the users and evaluating our haptic feedback system.

## 2 RELATED WORKS

Many research projects influence our work, and the work present in this paper is based on virtual reality with haptic feedbacks, immersive experience, and multiple tactile sensations.

### 2.1 Enhanced Virtual Environment with Haptic Feedbacks

To enhance the virtual environment (VE), wind feedback is usually used in VR. Head-mounted Wind [6] utilizes the wind arrays surrounded the user head for providing direction. Kojima et al. [7] utilizes speakers and air tubes placed beside the user ears to provide local wind. To simulate thermal sensation in VR, Thermovr [3] utilizes peltiers surrounded by the user eyes, which can provide contact tactile sensation of heating and cooling. Ambiotherm [8] and Season Traveller [9] utilize wearable devices to simulate the ambient temperature and wind condition in the VE. Jain et al. [10] also utilizes the motion-platform and peltiers to simulate the experience of scuba diving. Although wearable device can successfully provide different sensations in VR, most of the feedback only focus on partial body experience.

To create full or upper body experience, several works utilize stationary device. To recreate the wind sensation in VE, Moon et al. [11] and The VR Scooter [12] utilize the stationary device with fans to recreate the wind sensation. With the advance of VR-HMD, Birdly [13] utilizes a motion-platform with a fan in front of the user to provide a bird flying experience. Han et al. [14] utilize three electric fans to simulate the experience of flying with rope. Furthermore, to provide thermal sensation in VE, infrared light is another apparatus. Hülsmann et al. [15] utilize fans and infrared lamps on the top of the CAVE to enhance users' state of presence in VR application. Beside wind and thermal sensations, AoEs [16] also integrates the humidity sensation in their device, which can simulate two VEs simultaneously in a room-scale physical space with multiple tactile sensation. In addition to non-contact tactile sensation, the props from the physical space also is another information from the environment, which can provide contact tactile sensation such as chair, table, etc. Substitutional Reality [18] utilizes physical environment to create prop-based haptics. Chen et al. [1] has shown the potential of utilize human actuators and large-scale prop-based haptics for simulating the force feedback and structure of environments. In this paper, we focus on recreate the non-contact tactile sensation in VR.

### 2.2 Enhanced Immersive Interaction with Haptic Feedbacks

Haptic experience is various and complicate, human can perceive different multiple tactile sensation, which includes kinesthesia and cutaneous feedback from the object when the user doing their manipulation. Konyo et al. [18] utilize simple vibratory stimulations worn on the user finger to create the multiple tactile sensations such as roughness, pressure, and friction sensations. Altered Touch [19] utilizes peltier, motor and ribbon belt to alter the softness/hardness and thermal sensation. Wearable device also can enhance the VR experience. Lopes et al. [20, 21] utilizes electrical muscle stimulation to recreate physical impact, wall and heavy object. Synesthesia Suit [22] utilizes a cloth to create full body immersive experience by vibrations feedback. Besides wearable devices, several works [1, 23, 24] utilize different props or controller to enhance the immersive experience by passive haptic. NormalTouch and TextureTouch [5] has created the handheld VR controller to simulate the touching experience of 3D shape. Additionally, Fujinawa et al. [25] utilize haptic shape illusion to simulate the weight sensation in VR.

Although those haptic techniques successfully recreate the haptic feedbacks, they focus on one or few tactile sensations in VR. Our previous works [26-28] has shown the potential of utilizing the haptic feedbacks on the VR controller such as heat, air-blow, vibration, humidity and reaction force. Despite those haptic feedbacks can enhance the immersive experience when user manipulating the virtual object, those haptic technologies cannot enhance the experience when user moving around in the virtual space. This is the reason we integrate ubiquitous-based haptics and controller-based haptics to provide a complementary experience in VR.

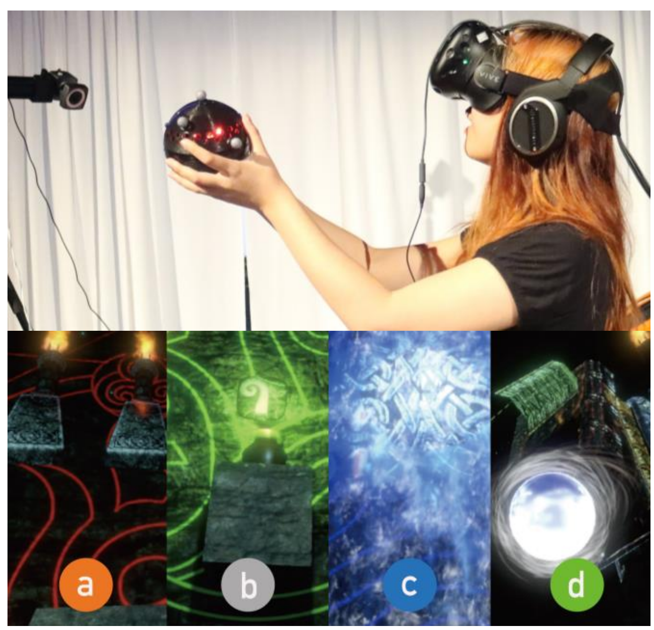


**Figure 2: Playing VR game with controller-based haptic: (a) Thermal sensation, (b) Vibration sensation, (c) Force sensation and (d) Wind sensation.**

## 3 EXPLORATORY OBSERVATION STUDY

In order to better understand the strengths and limitations of the stationary and handheld devices, we developed three VR applications with haptic feedbacks: (1) Entertainment, (2) Education and (3) Weather Simulation. Then, we demonstrated those applications with haptic device in three exhibitions separately [16, 26, 28], each participant experience about 8 minutes for an application.

### 3.1 Entertainment Application

Considering what application can be enhanced by multiple tactile sensations, VR game came to our minds first. In this game, players can play a role like an element bender who is able to absorb nature elements from certain scene objects with the orb-form controller [26] as Figure 2. While bending different nature elements, the player can perceive different tactile sensation from the controller. For example, using the controller to touch the torch, the orb will absorb the fire element. Then, the user will receive the visual and auditory feedback of fire and feeling the heat from the bottom of the controller. When the user bends the earth element, the controller creates vibration stimuli to stimulate the rock crashing. The water element would flow around the orb after the user absorbs it, then the controller will generate the centrifugal force. Finally, the controller creates wind feedback with the wind element absorbed. By combining those actions, the player needs to explore the virtual world through moving around himself, using controller to trigger the mechanism, receiving the new clue, and figuring out how to escape from the chamber.

### 3.2 Education Application

To find out in the other usage, the second application we developed is education application for learning the working progress of the blacksmith. We utilize an attachable case [28] on the VIVE Controller (Figure 3), which can provide 4 kinds of haptic feedback described as follow. This factory scene mainly uses "The Blacksmith: Environment [29]" unitypackage, which is a set of 3D models. In this application, we design a mission to let the users make an arrowhead. To experience the immersive interaction with haptic feedback, we simulate the step by step process of arrow manufacturing. Users will receive the haptic feedbacks in the process such as heating pieces of wrought iron into the furnace which could feel the heat from the iron, striking while the iron is hot which could feel the heat and reaction force, quenching the iron into a water sink which could feel the wind from the water sink, and polishing the iron on the grinding wheel which could feel the vibration.

### 3.3 Weather Simulation

The third application we developed is weather simulation with stationary haptic device [16] as Figure 4. In this application, four different virtual scenes are built to provide four kinds of tactile sensations in each scene. The user can utilize the portal to travel around the scenes, and they can experience the different tactile sensation from the VEs. For example, the users can feel energy-based heat when they stay in the temperate desert scene. In the river valley scene, they can feel the breeze and wet air. In the desert scene, they can feel hot air blow and energy-based heat. In the snow scene, they can feel the cold wind and wet air. Additionally, when the user moving around in the VE, the haptic modules will face to the user in the physical space.

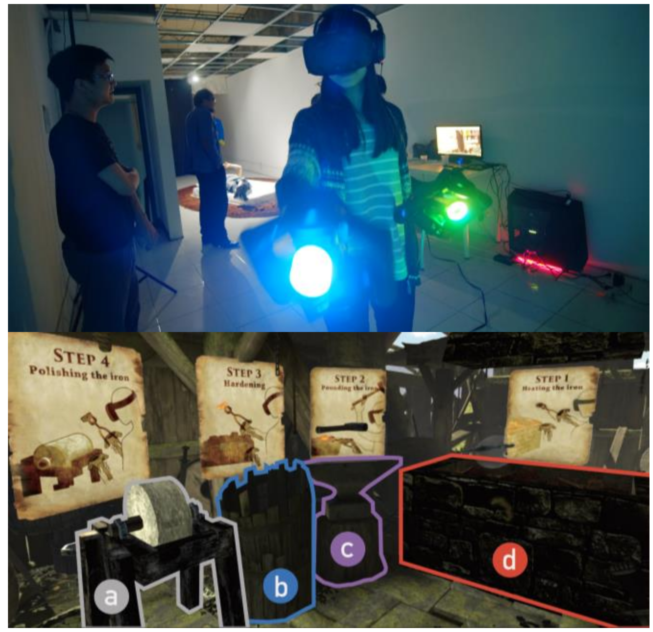


**Figure 3: Learning the working process of blacksmith in the VR with controller-based haptic: (a) Vibration feedback, (b) Force feedback, (c) Wind feedback and (d) Heat feedback.**

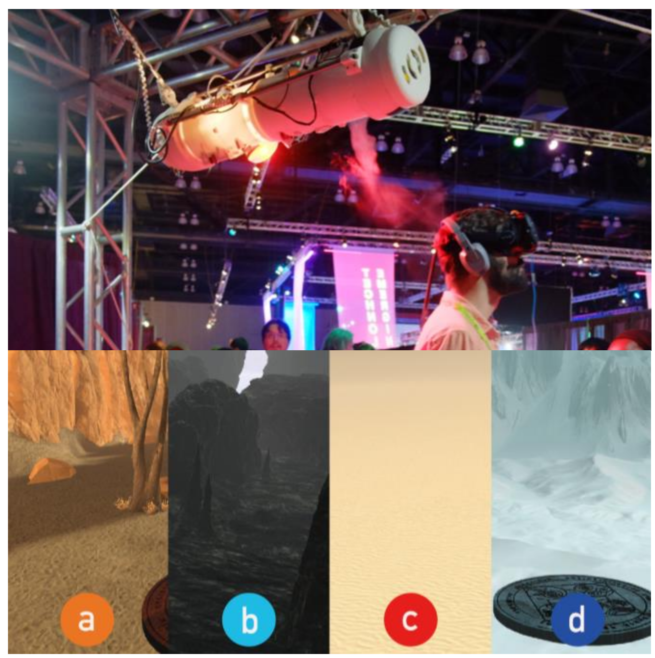


**Figure 4: Experience the environment in the weather simulation with ubiquitous-based haptics. (a) Temperate desert, (b) River valley, (c) Desert and (d) Snow mountain.**

### 3.4 Early User Response

Most of the participants enjoy playing our application with multiple tactile sensation. To understand the strengths and limitations of the stationary and handheld devices, we discussed as follow.

**3.4.1 Handheld Device.** In the application of entertainment and education, the users perceive the haptic feedbacks from the handheld device. The weight of the orb-form controller is 367g, the VIVE controller is 203g, and the attachable case is 642g. After the participants finished their task, some participants report that the VIVE controller with attachable case is too heavy. However, some participants enjoy the weight because it really like taking the hammer or iron clamp, which identify the weight sensation in the VR should take into consideration. Besides, the participants also mention the direction of the wind feedback is inconsistent when they are quenching the iron into a water sink. During the observation in entertainment application, some participants try to interact with the environment without the controller, which is the source when they trigger the tactile feedback. For example, the torch should be hot, but it is not. In the education application, we do observe the similar situation. When the users finished heating the wrought iron with right controller, they will use the left controller to hover the top of the furnace. However, they cannot feel the heat from the environment after they leave their controller from the furnace. Even though the furnace is so close, which should feel the heat from the user's right side. In both applications, we design the interaction related to water in VR. Due to the concern of the device are not waterproof, we did not adopt the humidity sensation. However, we use other metaphor to instead. Additionally, all the modules (except the wind feedback) on the both controllers are contact tactile feedback. The participants are exciting weather we can add more tactile sensations in VR, such as non-contact tactile sensation or humidity sensation.

**3.4.2 Stationary Device.** In the application of weather simulation, the users perceive the haptic feedbacks from the stationary device. The utility of stationary device is that the users are not necessary to use the controller or wear the glove/cloth to perceive the haptic feedbacks. With the stationary device, the users can perceive the haptic feedbacks when they are moving around. However, the effect is not strong enough. Some users reported that the haptic feedbacks on their hands were weak when they put their hands down.

## 4 DESIGN CONSIDERATION

To design a multiple tactile display, those works can be roughly divided into two approaches: (1) Simulating the sensations with one kind of actuator. Although this approach can simulate several levels of tactile feedbacks, most of them are the same type of tactile sensations. However, some examples can simulate an additional sensation. Such as human can feel the cutaneous feedback from the breeze blew, and kinesthesia feedback from the strong wind blow. It is great approach to enhance the diversity of tactile sensations in the tactile display. (2) Integrating different kinds of actuators in the device. The second approach is that utilizing the characteristic of each actuators and integrating those actuators to create realistic tactile sensations. There are several considerations and challenges when designing the multiple tactile display for VR system. In this paper, we focus on the last approach which can really simulate different type of tactile sensations.

### 4.1 Contact / Non-contact Tactile Sensation

Basically, tactile feedbacks can be classified into contact tactile sensation (CTS) and non-contact tactile sensation (NCTS). CTS represent that the user directly touches the source of feedback such as striking hammer, holding item and sitting on a chair. NCTS indicate that the user can feel the sensations from a non-contact source such as standing in the sun slash, trekking in the snow and walking in the wind. Additionally, thermal and humidity sensation could be contact or non-contact tactile sensation. For example, when the user is cooking, they can feel the heat from the handle of pan and from the oven. When the user taking a shower, it is CTS. When the user taking steam bath, it is NCTS. To design a haptic device with humidity sensation, the waterproof enclosure design is needed.

**Figure 5: In the immersive VR, the uses can perceive different tactile sensations from (a) the environment and (b) their manipulation.**

### 4.2 Fully / Partial Body Experience

To create the partial body experience with CTS, the actuator must cover on the part of the skin. In addition to creating the fully body experience with CTS, the actuator needs the ability to activate the whole body such as motion-platform. Besides, NCTS is easier to create the fully body experience, owing to the actuator utilize projecting from the source, which can be categorized into energy-based (such as infrared heat lamp) and flow-based (such as electronic fan). However, both actuators have the limitation of the effective area and the sensation gradually decreases by the distance [15]. This limitation is important to the designer because the user could move around in VR. Based on the size of effective area, the scenarios also can be subdivided into fully body experience and partial body experience (as Figure 5). For example, the sun, wind or rain usually have very large scale of effective area which can cover user's whole body. On the other hand, the effective area from the prop has a smaller effective area which only projecting to the partial body such as holding a boiling pot or an ice cream. Both fully and partial body experience are indispensable in a complementary immersive experience.

### 4.3 Static / Portable

When designing the haptic device for immersive VR, we need to consider what kinds of tactile sensation in real world that we want to simulate in VR and whether it is static or portable. To simulate environment which cannot be moved such as fixed table and oven, or cannot be directly touch such as sun, wind and rain. In most of cases, these kinds of virtual objects are big or ubiquitous, which can be simulated by the static haptic devices. However, the effective area problem is still existing it, and the direction of the tactile sensation are limited by the source position. Therefore, adding steerable structure can enhance the ability of device by shifting the effective area. Comparing to the static device, portable device can be taken or replaced, so the haptic feedbacks cannot be occluded by the user when they are moving around. This means that the virtual object also could be taken or replaced, which are suitable for simulating the tools or props in VR. Therefore, wireless and power consume should be taken into considerations when designing the device. Especially, the weight should be light or same as the physical object.

## 4.4 Scalable

To scale up immersive environments with haptic feedbacks, power consuming and devices communication are both serious issues. Whether extending the physical walking space, adding more portable props or simulating the strong tactile sensation, even activated two or more kinds of tactile sensations simultaneously, those enhancements need rich power supply to accomplish. Additionally, the VR system require a well network structure to communicate each device for the seamless interaction in the immersive VR.

# 5 HAPTIC FEEDBACKS SYSTEM

To demonstrate the feasibility of our concept, we design a haptic feedbacks system consist of ubiquitous-based haptics and controller-based haptics for enhancing the immersive environment and interaction. We utilize ubiquitous-based haptics to simulate the non-contact tactile sensations in immersive environment such as heat from the sun. Additionally, the controller-based haptics is design for enhancing the interaction when user manipulating with tools or props.

## 5.1 Ubiquitous-based Haptics

To create the locomotion experience with haptic feedbacks in a room-scale space, we need to simulate multiple tactile sensation in the VE individually or simultaneously when user is moving around. The detail of our design is as follows:

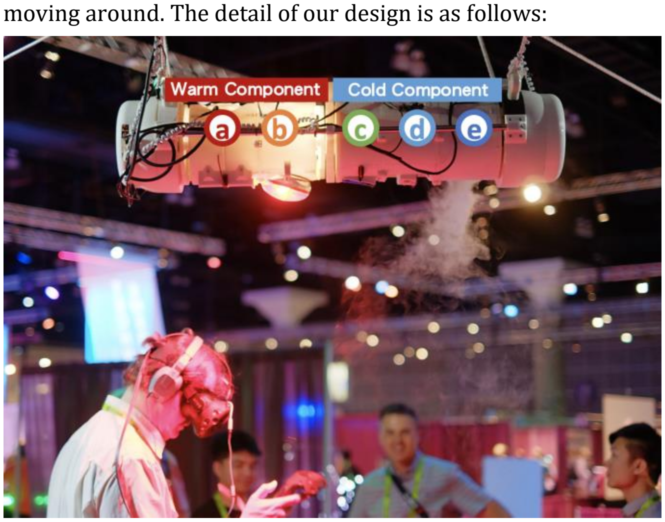


**Figure 6: Our ubiquitous-based haptic device: (a) Hot air module, (b) Heat module, (c) Wind blow module, (d) Rain drop module and (e) Mist module.**

**5.1.1 Haptic Modules.** This device is divided into two parts, the warm component and the cold component as Figure 6. We measured the temperature at 80cm far from the bottom of the device, which is the height from the center of the user upper body. The warm component (Figure 7) consists of two modules: (1) heat module and (2) hot air module. The heat module is equipped with a 250W heat light which can make the temperature increase from room temperature 22°C to 25°C. The hot air module utilizes a 1300w heat blower and a fan shutter, which not only provides the wind but also can increases the temperature to 38°C. Besides, when the both modules are activated the sources of the heat are over than 100°C. Therefore, to screw the heat light on the module, we utilize ceramic lamp holder and epoxy putty, which are deformation resistance and high temperature resistant. For the heat blower and the fan shutter, we utilize the heat insulation foam to prevent the heat transfer.

The cold component consists of three modules: (1) mist module, (2) rain drop module and (3) wind module. The mist module (Figure 8a) utilize four ultrasonic mist makers and an electric fan (3300 rpm) to create the mist. The mist makers are placed in a water tank which can store 1L of water. The top of the tank is for storing the mist. The fan is on the top of module which can flow out the mist through the drain. The rain drop module is similar to the mist module but utilizes three micro-aperture atomizers on the bottom of the bottle which directly spray the water. The bottle can store 600ml water. The wind module is equipped with a 12V, 8600 rpm electric fan which provides the highest wind speed 11.5m/s. The power consuming of cold component is 133w, and the overall power consuming of all haptic modules is 1683w.

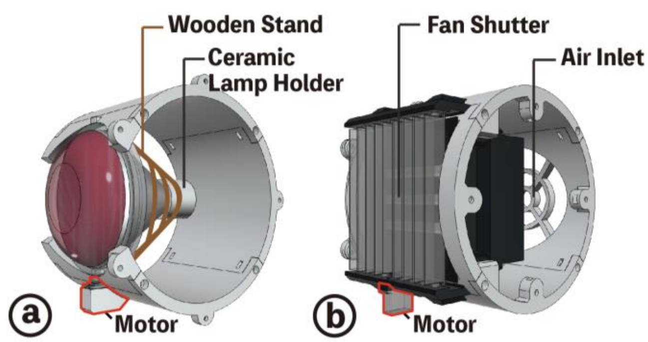


**Figure 7: The hardware design of warm component: (a) Heat light and (b) Heat blower.**

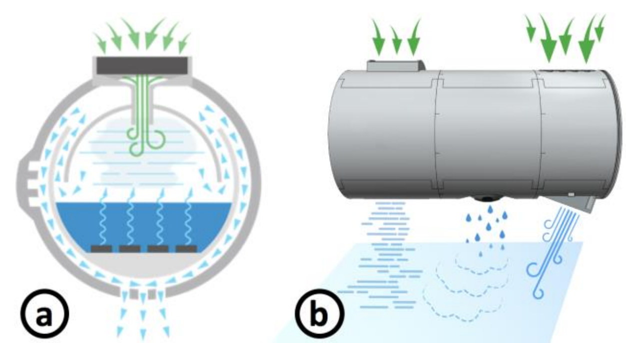


**Figure 8: The hardware design of cold component: (a) Mist creator and (b) Modules combination.**

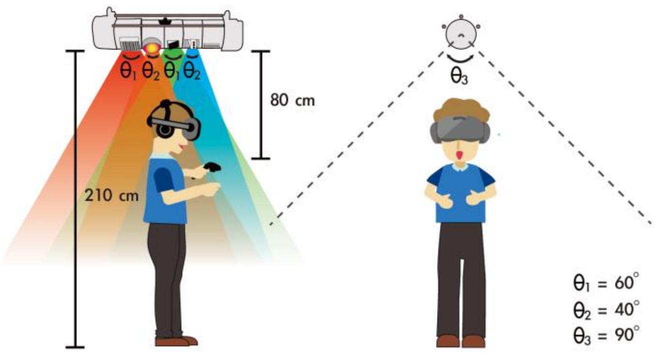


**Figure 9: The effect area of ubiquitous-based haptics.**

**5.1.2 Combination of Modules.** With different combinations of the modules, our device can simulate varying degrees of cold environment or heat environment with breeze. For example, we activate the mist module to simulate a cool feeling (from room temperature 22°C to 19.66°C). While activating the three modules at the same time (Figure 8b), our device can simulate even cooler and wetter environment (from 22°C to 18°C). Additionally, we separate the module using the airflow in odd number to prevent the mutual influence, and the air-admitting surface should be big enough.

**5.1.3 Steerable Structure**. With steerable structure, the effect area can be extended by changing the project direction. LuminAR [30], Zerroug et al. [31] and Wilson et al. [32] utilize steerable structure to extend augmented screen in augmented reality application. AIRREAL [33] also utilize steerable structure to shoot the air jet for providing tactile sensation. The hardware design of our steerable haptics device is shown in Figure 9. The size of the device is 108cm x 30cm x 27cm, and the weight is 15kg. Both cold component and warm component has their own axis of rotation, which can rotate individually, and the maximum rotation is 90 degrees. To rotate the component, we utilize a stepper motor, a high-torque gear and two bearing on each side of component. Besides, the water tank is fixed inside of device, so the motor does not have to lift the tank. In each module, except mist module, all other module has their own axis of rotation via a servo motor on the bottom of the module, which the maximum rotation is 40 or 60 degrees due to the structural restriction. With two axes, the effect area is illustrated as Figure 9. To make sure the activated modules face the user directly, we implement a tracking system based on the VR-HMD. To calibrate the device, we utilize the VR controller to markup the end of the both side of the device. Then, the system can align the physical device to the virtual world. Therefore, our system can provide haptic feedback on the user body or hand when they are wearing the VR-HMD or holding the VR controller.

## 5.2 Controller-based Haptics

To enhance the interaction in the immersive environment, we design a VR controller with multiple tactile sensations, which is wireless and trackable. So, the user can manipulate freely when facing to any direction. Our hardware design of controller-based haptics is shown in Figure 10, which consist mainly of two parts: (1) Haptic Module and (2) Attachable Structure.


**Figure 10: Our controller-based haptics device: (a) Haptic module, (b) Attachable structure and (c) Connecter for VIVE tracker.**

**5.2.1 Haptic Modules.** We develop four kinds of haptic modules (Figure 11) for our VR controller, which is (a) heat module, (b) wind module, (c) motor module and (d) wet module. The weight of the heat module is 31g, which utilize halogen lamp to create temperature sensation. The wind module (66g) utilize 5V, 7cm electronical fans to create the local wind feedback. The motor module (46g) utilize Ultra Dash Motor to create the force feedback. The wet module (68g) could store 60ml of water, which utilize micro-aperture atomizers to create the mist spray on the user hand.

**5.2.2 Attachable Structure.** The concept of the attachable haptics is that the user can change the module base on the application they used. So, we design the attachable structure on our controller (Figure 11) and haptic modules mentioned in the previous section. On the controller, there have five slots for the haptic modules to simulate different source direction. The size of the device is 11.5cm x 26.5cm x 11cm, and the weight is 350g including two 3.7v batteries. On each slot, there have four magnets for attaching and detaching the modules, so the user can interchange these modules. After attaching the haptic modules on the structure, we need to configure the placement of the module in our system. To track the controller, we utilize VIVE tracker (91g), which screw on the top of our controller with hexagon nut. With four kinds of modules, the overall weight is 652g. Finally, by the combinations between each

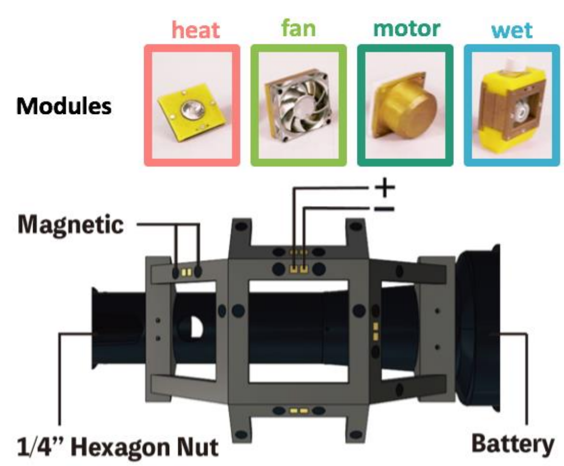


**Figure 11: Hardware design of attachable modules and structure.**

module, user can perceive the related haptic when manipulating in the immersive environment.

## 5.3 Implementation

The main structure of our haptic feedbacks system is made by 3D printer. Although the 3D printer is a convenient tool for digital manufacturing, they do have some limitation. Due to the limitation of print area and the concern of deformation of printing big object, we need to divide the device into several parts, and compose it together after we print it. The material we use is PLA, which the material shrinkage rates is lower than ABS. This makes the success rate higher when printing objects. Hence, we can save more time when we have lots of 3D object parts need to be printed. However, the glass transition temperature of PLA is around 60°C~65°C, which can cause the structure deformed again. Therefore, we adopted deformation resistance and high temperature resistant material mention in section 5.1.1 to prevent the heat source directly contact to the structure made by PLA material. Additionally, for objects in contact with the water, we paint a layer of epoxy on the PLA material to prevent water leak.

Our application executes on a VR-ready computer, which equip with a i7-6700 processor, a GTX1080 graphic card and 16 GB RAM. The overall rendering performance is >90 fps. The VR-HMD we used is HTC VIVE Pro. The entire software system and applications is developed based on the Unity 2017. To control two haptic devices, in each device, we utilize an Arduino with Bluetooth for system integration and wireless connection.

## 5.4 Interaction Design with Hybrid-Haptics

Our hybrid-haptic feedback system consists of ubiquitous-based haptics and controller-based haptics. To enhance the immersive experience with multiple tactile sensation, there were four kinds of interaction as Figure 12. Those combinations could consist of same or different tactile sensations.

**5.4.1 Blending Two Haptic Feedback with Full Body Experience.** As Figure 12a, this is the main concept of our haptic system, which the user is holding a handheld device with haptic, and his body is covered by the ubiquitous-based haptics. The stationary device simulates the haptic feedbacks from the immersive environment. The handheld device simulates the feedback from the manipulation.

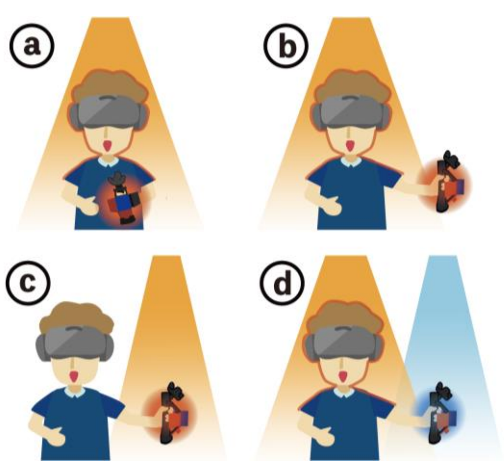


**Figure 12: Enhanced Immersive Experience with Multiple Tactile Sensation: (a)(b)(c) Blending two sources of feedback, and (d) Blending three sources of feedback.**

**5.4.2 Extending the Effect Area by the Controller.** As Figure 12b, the user body is covered by the ubiquitous-based haptics, and his hand is holding a handheld device with haptic on the boundary of the ubiquitous-based haptics. This hybrid-haptic could enhance the experience at the boundary of the effect area via the user perception.

**5.4.3 Enhancing the Haptic Feedback from the Controller by the Stationary Device.** As Figure 12c, the user is holding a handheld device with haptic, and his hand and arm are covered by the ubiquitous-based haptics. This interaction utilizes the physiological phenomenon of thermal referral [34], which occurs when stimulation at one point on the skin is experienced at another closed location.

**5.4.4 Blending Extended Haptic with Stationary Device.** This hybrid-haptic (Figure 12d) is more like the combination of Figure 12b and Figure 12c. The user body is covered by the ubiquitous-based haptics, and his hand is holding a handheld device with haptic, which his hand and arm are covered by another ubiquitous-based haptics. This hybrid-haptic could be refer to as "a person opens the refrigerator in the summer." Due to the human receptor only can feel the relative temperature, the contrast between cold and warm environment can enhance the user perception.

## 6 USER STUDY

We conducted a user study to validate our haptic feedbacks system with the following conditions: (1) Without Haptic: experiencing without any non-contact tactile sensations; (2) Controller-based Haptics: experiencing with the haptic feedback on the controller only; (3) Ubiquitous-based Haptics: experiencing with the haptic feedback of the environment provided by stationary device only; (4) Hybrid-Haptics: experiencing with haptic feedbacks from the controller and the stationary device. This study was conducted as a RM-ANOVA with post-hoc pairwise Tukey's tests. The order was counterbalanced by the Latin-square design. We recruited 16 participants (8 males and 8 females) from our institute. Their ages range from 20 to 29 years old (mean = 23, SD = 2.19). Their height ranges between 154 to 181.5 cm (mean = 167.81, SD = 7.46). Seven participants had never worn an HMD before. The other nine participants had VR experience, and five of them had the experience of developing VR application (without haptic feedback).

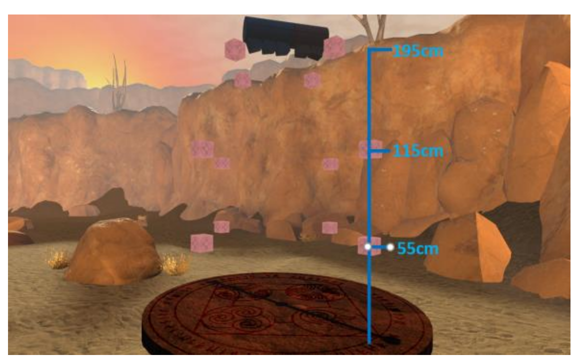


**Figure 13: The placement of the cubes**

Table 1: The design of haptic feedback in each scene.

| | Ubiquitous-based | | | | | Controller-based | | |
|---|---|---|---|---|---|---|---|---|
| | Hot Air | Heat | Wind Blow | Rain Drop | Mist | Heat | Wind Blow | Wet Spray |
| (1) | | | | | | | | |
| (2) | | ✔ | | | | ✔ | | |
| (3) | | | Weak | # | ✔ | | | ✔ |
| (4) | ✔ | ✔ | | | | ✔ | | |
| (5) | | | Strong | ※ | ✔ | | ✔ | ✔ |

#Intermittently spray; ※Continuously spray.

In each interface, participants could walk around in the virtual space freely and they experienced the virtual world by means of a VIVE HMD with earphones and our haptic devices. There were totally 5 scenes (same as the application in section 3.3) in the experiment. At the beginning, participant will stay in the scene of preparing room. The participant should finish the task by touching all the element cubes in the scene with controller, then the participant will teleport to the next scene. There were 12 cubes in each scene (as Figure 13): 4 at the top area, 4 at the middle area, and the last 4 at the low area. When touching the cube, the controller would give the corresponding haptic feedback if the interface condition allows controller's haptic feedback. After touching the last cube in the scene, the portal will open, and participant can walk into the next scene. Following is the order of scenes: (1) Preparing Room; (2) Temperate Desert; (3) River Valley; (4) Desert; (5) Snow Mountain; (6) Preparing Room. The design of the haptic feedback in each scene shows at Table 1. Finally, after completing each interface, they filled in a custom questionnaire, which use 7-point Likert scale (7 = totally agree, 1 = totally disagree), and a short interview are made.

## 6.1 Result

Figure 14~17 shows the result of our study. Asterisks and red lines indicate occurrence of significance difference. Figure 14 shows the scores overview. Participants rated their experience as more enjoyment, realistic and immersion when they were in the hybrid-haptic feedback condition. Figure 15 shows the scores of different feedbacks. Participants enjoyed their experience more in the hybrid-haptic feedback condition, especially with mist feedback. Figure 16 shows the scores of each virtual scene. Participants enjoyed their experience more in the hybrid-haptic feedback condition, especially in the snow mountain. Figure 17 shows the scores when touching the cubes at different area. When the distance is far from the source, the participants rated their experience as less enjoyment.

## 6.2 Discussion

In our study, the environmental feedback is ceaseless and continuous. On the other hand, the feedback on the controller is triggered. The participants can surely perceive their corresponding feedback and summary their feeling is that human can distinguish whether the tactile feedback comes from the environment or from their own triggering. P5 said, "Environmental feedback is continuous, allowing me to have an immersive effect without moving. When I touched the cube element in the scene that let me truly feel that I had touched it."

**6.2.1 Hybrid-Haptic Feedbacks.** With any one of haptic device, participant feel more engaging. When experiencing our VR system, the hybrid-haptic feedback can achieve complementary effects. It can be confirmed on the result of enjoyment and quality (Figure 14). When we asked the participants about the thoughts afterwards, P4 said, "With these two feedback devices, I will be more immersed in the VR environment.", and P7 mentioned that "I feel less sense of reality after missing the feedback on controller." Additionally, P3 said, "It is really cool when both of them are on!" In our result, the interface of ubiquitous-based haptics and hybrid-haptic did not shown significant different on the score of the immersion and the realism, but the scores are high. The reason is that most of the immersion and the realism are from the environment, so the controller-based haptic could not enhance too much.

**6.2.2 Haptic Modules and Multisensory Feedback.** In our result (Figure 15), most of the user enjoy the humidity sensation. Although human do not have a humidity receptor in the skin, they still can feel the wetness via thermal sensation and mechanosensory [35]. Additionally, the participants have strong feeling in cold and wet environment such as river valley and snow mountain, which the score of cold scenes is higher than hot scenes (Figure 16). Most of the participants (10/16) mentioned that it is significance different when they perceive the mist feedback in the immersive environment. P11 said that he feels strongly different when hybrid-haptic feedbacks are off, especially in the snow mountain. Furthermore, participants are more likely to have ubiquitous-based haptics. When using controller-based haptic device only, the effect of wind and mist is too abrupt. Nevertheless, the effect can be strengthened in the hybrid-haptic condition. That is why the scores between controller-based haptics and hybrid-haptics are significantly

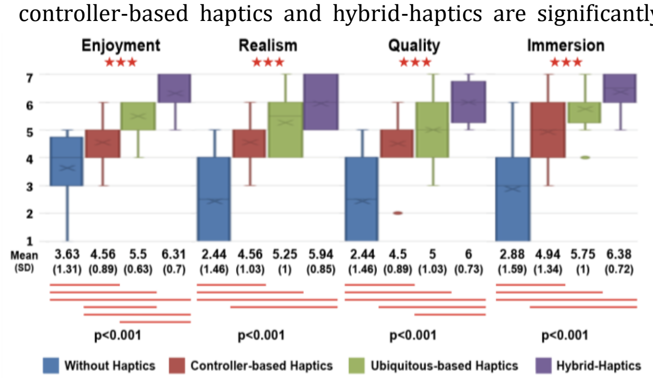


**Figure 14: The result of enjoyment, realistic, quality and immersion.**

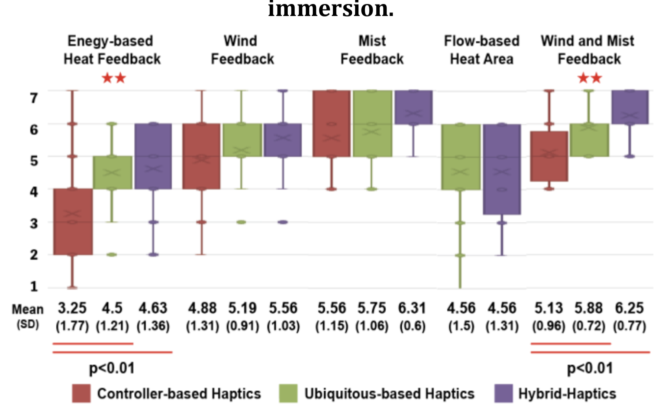


**Figure 15: The performance of five kinds of haptic feedback.**

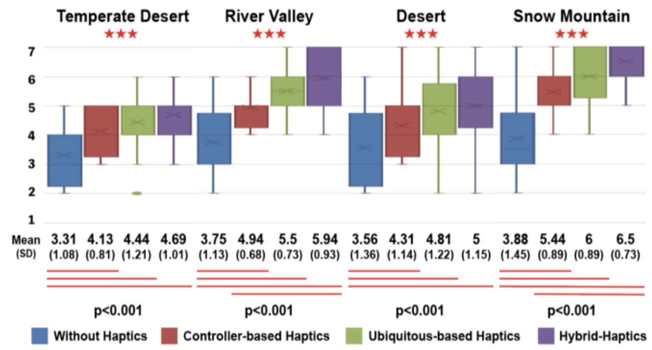


**Figure 16: The result of multisensory feedback design in each scene.**

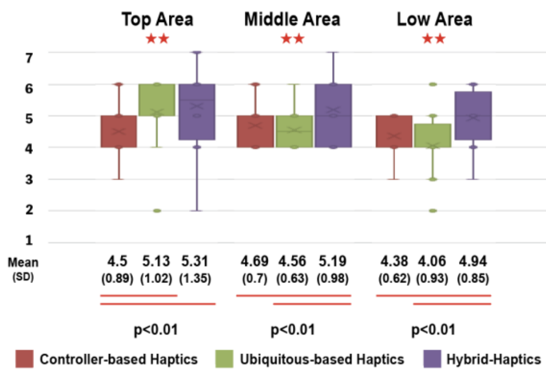


**Figure 17: The result of touching the cube from top area, middle area and low area.**

different in cold scene (shown in figure 16). P14 said "The water spraying on the controller is too much, but with the ubiquitous-based haptic device, it is quite adequate."

In the result of the warm component, the standard deviation of the score is high. Although most of the participant could feel the energy-based heat and the flow-based heat from the stationary device, the thermal energy lost very quickly in the air. On the controller-based haptics, the participant could slightly conscious something happened on their hand, but some of the participants (4/16) mentioned that the feedback of the energy-based heat from the controller is not heat enough. According to the users feedback, we found out that the description of the heat is quite different between the users. Comparing the perception of heat and cold, the users have a higher consistency in the comments on cold feedback.

**6.2.3 Enhanced Immersive Experience.** In Figure 17, as expected, when the participants used the interface of controller-based haptics, the average score of each area are the same. When using the interface of ubiquitous-based haptics, the average score will decrease followed by the distance from the stationary device to the ground. Additionally, when they touch the cube at the top area, participants whose arm is longer may leave the effect area. Hence, the standard deviation of the score from top area is high. However, with hybrid-haptic interface, it could have better performance, which the result has shown the significant difference when the participants touch the cubes at the middle and the low area. In the case of touching cube from the middle area, the users' hand could be covered by the effect area, which the case is like Figure 12a. When touching the cube from low area, this case is like Figure 12b. It will have an extended effect in the experience because there still is haptic feedback on the controller. P14 said, "When I move the controller down, there is a feeling of bringing the upper tactile feedback back down."

## 7 LIMITATION AND CHALLENGES

In our study, we only evaluated our hybrid-haptic feedback system for the interaction in the warm environment and cold environment, which the combination of the tactile sensation is basically the same in each scene (Table 1). Although those related works and this paper have been very successful at giving users multiple tactile sensations by the haptic devices, recreating the haptic experience in VR is still a challenge [36]. This work only enables the multiple tactile sensation that mention in the paper to show the potential of interaction design with hybrid-haptic. The further studies are needed to understand the tactile illusions for optimization the haptic feedback in VR.

### 7.1 Area of Effect and Efficiency

Our goal is to provide the ubiquitous-based haptics, which could cover the whole body. Although the steerable structure can extend the area of effect, the efficiency of haptic module only could cover upper body as Figure 9, and their still has some limitations describe below. Both energy-based heat and flow-based heat decreases too fast. Due to the stationary device are hanged on the top of the user, the haptic feedback only available on the user upper body, especially, exposed skin area. The user height and long sleeve may affect the user experience. This is the trade-off between performance and power consumption, which is the challenge that how to precisely provide non-contact tactile sensation. Additionally, the cold and warm components are fixed on the placement, which cannot be switch. This can be improved by adding a rotation axis that perpendicular to the ground. Besides, our ubiquitous-based haptics focus on the entire environment (such as weather) when the users standing on the ground, so, if the direction from the source is emphasis and not from the top (over 45 degrees [11]), it might not suitable for our system, such as free fall. Despite this can be directly solved by setting up more devices based on the situation from the environment, it is still a research issue that how to provide enough ubiquitous-based haptic and need to be figured out what is the universal solution.

### 7.2 Universal Controller in VR

Human hand has lots of joint and nerve ending in the fingertips, which can precisely use the tools and complete the meticulous tasks. This is the common way that we explore the real world. Compared to the ability of hands, our controller only shown the potential of adding multiple tactile sensation that mention in our paper. Furthermore, in our study, we only investigate the non-contact tactile sensation and the combination of ubiquitous-based haptics and controller-based haptics in VR, which are wind sensations, thermal sensations, humidity sensations and their combination. The heat module and wind module on the attachable case can be improved by utilizing high efficiency module with pre-activation mechanism.

To design a universal controller included all the tactile sensation that human hands can perceive is a challenge. Take the balance between weight and power consumption, we cannot integrate all the module as much as we can and might do not need all of it. Therefore, the concept of attachable device will might be the chance. However, before we do the iterative design, we need to investigate the ability of hands for perceiving each different tactile sensation first, which include the tactile direction discrimination, the perceptual-cognitive model, etc.

## 8 CONCLUSION AND FUTURE WORK

In this paper, we presented Haptic Around, a hybrid-haptic feedback system to recreate multiple tactile sensations for immersive environment and interaction in VR. Furthermore, with our haptic technique, the users could perceive partial body and upper body experience simultaneously. Our work contributes the insight of exploratory observation study, design considerations, system design and implementation details. In the user study, the results have shown that it is a potential approach for enhancing the immersive experience. In our future work, we will optimize both devices. For the ubiquitous-based haptics, we focus on enhance each haptic module and the steerable structure to extend the effect area and the efficiency. For the controller-based haptic, we will develop a spherical stationary device with array modules for human hand, then investigate the ability of perceiving different tactile sensations. Finally, we will conduct further studies for investigate the complementary effect and the tactile illusions in VR for both partial and full body experiences.

## ACKNOWLEDGMENTS

This research was supported in part by the Ministry of Science and Technology of Taiwan under the grant MOST 105-2218-E-009-025-.

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