WriMouCon: Wrist-Mounted Haptic Controller for Rendering Physical Properties in Virtual Reality

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***Abstract*—For immersive Virtual Reality (VR), the need for effective and precise haptic feedback is increasing. This paper proposes a wrist-mounted haptic controller that provides direct feedback to the palm for rendering various physical properties. We conducted various experiments that demonstrated the effectiveness and accuracy of our device. First, we found that our device renders negligible force (0.02 N) to the user in the free-hand situation. Second, we confirm that our device renders physical properties with high accuracy (within 6%) by using Force Sensing Resistor (FSR). Finally, we present the minimum force feedback threshold and difference threshold of the proposed device. From the results of perceptual experiments, we suggest a design guideline for using the proposed prototype.**

***Index Terms*—Haptic Feedback, Wearable Devices, Haptic Rendering**

I. INTRODUCTION

The recent VR technologies make the user experience more realistic. Enhanced display and sound technology provide a visually and audibly immersive experience in VR spaces. Moreover, the recent VR controller works as both an input and output device, including an enhanced haptic experience [1]. To this end, overall VR interfaces focus on providing a realistic experience incorporating various types of sensory feedback [2]. Still, only a few commercial VR products fully support haptic feedback interfaces. This is mainly due to the fact that the current haptic interfaces require expensive and complex external devices [3], [4].

Nevertheless, VR controllers with haptic feedback are essential for experiencing realistic virtual content. Previous works demonstrate haptic feedback controllers with various shapes and functions including a handheld type [5] and a wearable type [6]. In terms of application, researchers have utilized haptic controllers for various hand interactions such as rendering textures [7], shapes [8], grasp [9], and squeeze [10]. Still, existing approaches have a relatively bulky form factor which is hard to be used for everyday purposes.

To this end, the haptic system with a simple structure to support a wide range of applications (e.g. precise force control) was explored such as rotating wheel [7] and locking slider design [11]. Although these works were lightweight and easy to use with a simplified structure, a specific hand posture (*e.g.*, grabbing with thumb and index or tapping with index) is needed to receive the intended feedback.

In our work, we propose a wrist-mounted VR haptic controller that supports various force-based interactions. We employ a simplified hardware design to maximize the range of motion for the hand without losing precise control. Here, our device provides detailed force feedback to the palm to render the physical properties of objects or environments including weight, stiffness, and air resistance. Rendering physical properties allow us to distinguish objects of the same size, but with different physical properties. Also, our design allows users to freely move their hands while transmitting effective palmar force for rendering the physical properties of virtual objects.

Our paper presents the following contributions:

- A 1-link manipulator-based motorized haptic controller that allows free hand posture/motion while providing precise palmar force feedback.
- Force feedback framework that computes virtual object's properties and converts them into precise motor control.
- Design guideline to recognize and distinguish physical properties of virtual objects using the proposed force feedback system.

II. RELATED WORK

A. Haptic Devices for Hand Interaction in VR

Researchers have studied handheld haptic devices since they support rich input/output performance without cumbersome installation requirements. Typically, handheld devices offer haptic feedback through the user's palm or fingers [7], [12]. With these advantages, a number of handheld haptic VR controllers that render expressive haptic sensations have recently been studied [8], [13]. However, users need to firmly hold the handheld devices to experience the designated haptic feedback that aligns with the VR interactions.

Previously, researchers often came up with an exoskeleton-type haptic feedback device that wraps around the whole hand or each finger [14], [15]. Although these devices transmit accurate forces to each finger joint, it is difficult to guarantee system durability due to the excessively complex mechanical structures. To overcome this, wearable devices in the form of concentrating and transmitting haptic feedback on the palm have been suggested [16]–[18]. For example, previous works proposed adding inflatable air-pocket devices in the center of the palm for enhancing grasping interaction [19], [20]. Although the palmar force-focused design has the disadvantage of not being able to transfer the force to the desired point other than the palm, our proposed controller is designed in the direction of focusing haptic feedback on the sensitive area of the palm. In addition, our design has an advantage in forming instant force feedback since our device is always in close contact with the hand during operation.

B. Rendering Physical Property in Virtual Reality

To provide a realistic VR experience, users should feel various physical properties in VR like the real world. For example, the users should feel the weight when lifting a virtual object. The system could easily compute the force required to create weight sensation using the dynamic equation (Eq.1). Here, F_i refers to a force that needs to be generated based on g, a, and M which denote gravitational acceleration, the object's acceleration, and the object's inertia accordingly. Previous works showed that either changing the inertial value of the controller body [21], [22] or rendering the force based on the inertia [11], [23] could bring realistic weight sensation.

$$F_i = M(g+a) \tag{1}$$

To create a realistic elasticity sensation, the haptic feedback should vary depending on the displacement and hardness of the virtual object when interacting with the user. Researchers have used Hooke's law (Eq.2) to compute the output force (F_e) which is proportional to the displacement of the object(x) and constant stiffness factor (K). To produce haptic feedback based on the given stiffness, previous works generate force through either an integrated elastic component [24], [25] or a motor system [26], [27].

$$F_e = Kx \tag{2}$$

The viscosity often refers to a flow resistance from the fluid. In a VR environment consisting of wind or water, the viscosity could create an additional force for the user on top of other physical properties. Here, Eq.3 computes resistance force to the fluid (F_v) which is proportional to the velocity of the environmental fluid (v_{env}) and a virtual object (v). B denotes the coefficient of fluid resistance or the viscosity coefficient of the fluid. We applied the simplified Stokes' law for the convenience of implementation and experimentation. Previously, researchers realize the viscosity sensation by dynamically adjusting the surface area of the controller body [28] or employing propeller-induced propulsive force [29], [30].

$$F_v = B(v_{env}+v) \tag{3}$$

In this work, we propose a wrist-mounted controller that implements the above-mentioned physical properties including inertia, elasticity, and viscosity. To do this, we employ a force feedback system including all physical properties as shown in Eq.4.

$$F_{ref} = M(g+a) + Kx + B(v_{env}+v) \tag{4}$$

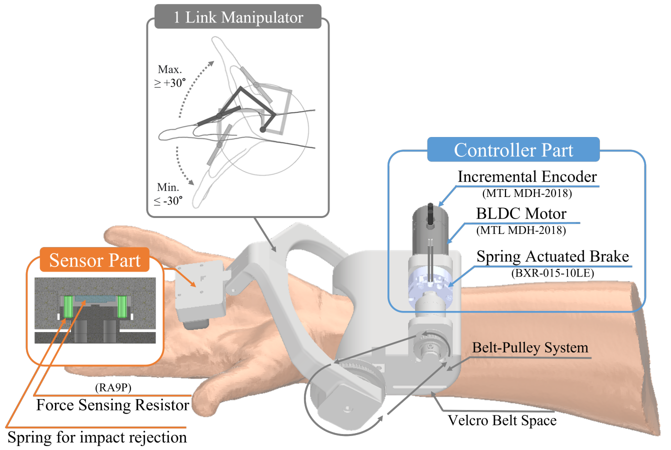

Fig. 1. We pick a precise torque control embedded BLDC motor as a fore source where the belt-pulley system amplifies the torque. A 1-link manipulator converts the amplified torque into a force and drives the device to the palm. Here, the FSR sensor functions as a typical switch where an integrated spring structure reduces the mechanical impact on the sensor during operation.

III. WRIST-MOUNTED HAPTIC VR CONTROLLER

Our design goal is to render force and impedance to the user's hand without limiting the range of motion. It is often challenging for a wearable device to secure enough space for moving hands. This often leads to either constraining the range of the motion or requiring specific hand posture to receive intended haptic feedback. To maximize the working space for the hand, we chose a simplified 1-link manipulator design with the rotation axis located at the center of the wrist. As shown in Figure 1, $\pm 30^\circ$ is the range of angle at which the motor operates accurately. Our prototype does not limit the degree of freedom for the user's wrist motion when a motor is off. Moreover, our approach enables instant force feedback to be compared to previous work [17] since the device is always in close contact with the palm.

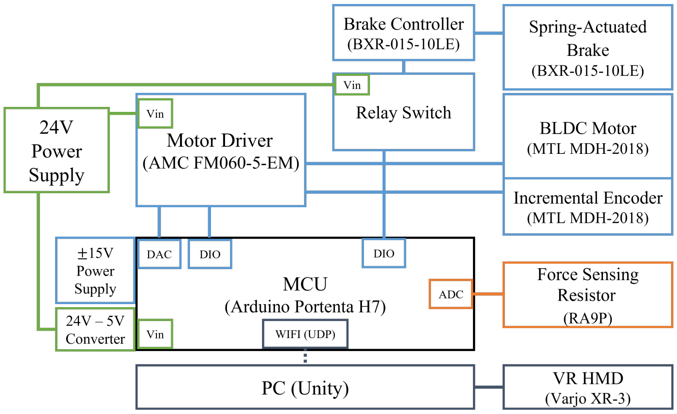

Fig. 2. System configuration of our work. The motor driver and brake controller operate independently. VR scene runs on a PC that is connected to VR HMD.

TABLE I
OVERALL CONTROLLER SPECIFICATION

Weight	386 g
Operating Voltage	24 V
Rated / Peak Current	1.4 / 5.6 A
Torque Constant (Motor)	0.023 Nm/A
Rated / Peak Torque (Motor)	0.03 / 0.13 Nm
Rated Ang. Velocity (Motor)	157.08 rad/s
Gear Ratio	1:2.609
Rated / Peak Torque (with Gear)	0.078 / 0.34 Nm
Rated / Peak Ang. Velocity (with Gear)	60.21 rad/s
Distance from Gear to End-point	92.5 mm
Rated / Peak Force (End-point)	0.843 / 3.68 N
Rated Lin. Velocity (End-point)	5.57 m/s

A. Hardware Implementation

We design and build the wrist-mounted haptic controller to deliver dynamic force interaction to the palm as shown in Figure 1. We came up with a wrist-wearable controller consisting of a 1-link manipulator operated with a belt-pulley system. We take special consideration in choosing the effective location for force feedback. According to the [31], we designed the wrist-mounted haptic controller to deliver force to the right below anterior digital regions which are known to be sensitive. The contact area is 23 $mm \times 27\ mm$.

Figure 2 shows overall hardware configuration with Arduino Portenta H7 (STM32H747 with 480 MHz Cortex-M7 & 240 MHz Cortex-M4). The system contains a BLDC motor (MTL's MDH-2018, 33.6 W) and FSR (SMarvelDex's RA9P). The brake (Mikipulley's BXR-015-10LE, 16.8 W) is controlled using a relay (SONGLERELAY's SRD-05VDC-SL-C). Our system communicates with the PC via Wi-Fi and we use Varjo XR-3 as our VR HMD. Our prototype specification is shown in Table I. We embedded our brake to improve the power efficiency of our devices.

B. Haptic Feedback Control

Figure 3 shows the overall feedback control workflow to compute real-time inertia, viscosity, and elasticity based on the input force from a VR scene. The physical characteristics of each virtual object were formed through a force according to the user's hand motion. In more detail, after users wear the prototypes and start interacting with VR, Unity detects the contact on Unity Avatar's palm collision with VR objects. After detecting the collision, Force input is calculated with physical properties, and the user's hand movement. Then, the data flow delay from Unity to Arduino Portenta H7 is less than 50 ms. We use a PI control method by using a motor's current value to control our output.

IV. TECHNICAL EVALUATION

Rendering haptic feedback increases the user's immersion. Also, it is important to quantify the characteristics of devices. To confirm the stability and the rendering performance of the proposed haptic system, we carried out technical evaluations. These include zero-force control stability and physical properties rendering evaluations. We use Varjo XR-3 equipped with a Leap Motion hand tracking system and force sensor (SIGLETACT, CS8-10N) as shown in Figure 4.

A. Experiment 1: Zero-Force Control

Our device operates a haptic feedback control system while wearing the device. Therefore, it is crucial to confirm whether our device creates any unwanted force on the palm if no force feedback is applied. When there is no force feedback applied, our prototype still transmits force to keep the 0 N state rather than simply turning off the control system. Thus, a zero-force control experiment would verify the performance of our proposed control system.

Setup: In this experiment, The subject was equipped with the devices. Before the experiment, we set zero-force control by setting 0 N as our target force. The subject freely moves the hand while wearing the device. We calculate the applied force by measuring the internal current of the motor driver because current values are freer than FSR from noise caused by mechanical disturbance. Also, we use data from the encoder mounted on the motor to compute the velocity of the End-point.

Result: Although our experiment's name is zero force control, we intended to keep the hand following by giving the user a force that was difficult to recognize based on our perceptual experiments. As shown in Figure 5, we evaluate our device's zero-force control when the user moves the hand very quickly. The results show that the measured force stayed within 0.01 N when there was no external movement. Therefore, 0.01 N represents the baseline noise of our system.

When we applied the external movement up to 1.6 m/s, the measured force still stayed within 0.02 N Because the minimum force feedback threshold is 0.114 N from our following perception experiment, 0.02 N is negligible external force feedback. Our result confirmed that the proposed control system adds less than 0.01 N to the baseline system during operation. This means when users try to rotate the hand up in Figure 4, it is natural that because of gravity users have to feel some resistance from the controller. With zero force control, however, the motor rotates according to hand movements so the user feels less resistance.

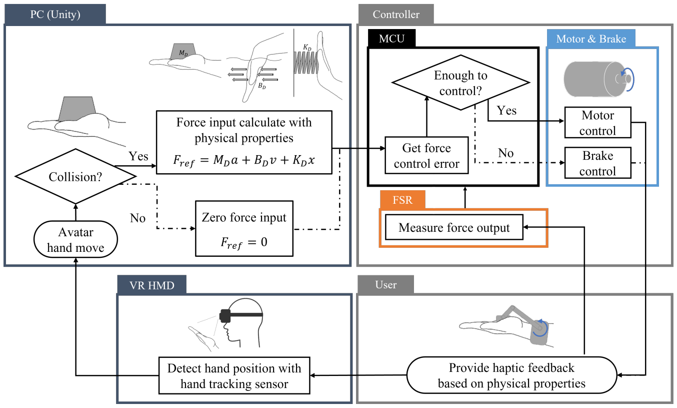

Fig. 3. Overall workflow of WriMouCon. We configure a closed-loop workflow where the haptic feedback force is computed based on the user's hand-tracking.

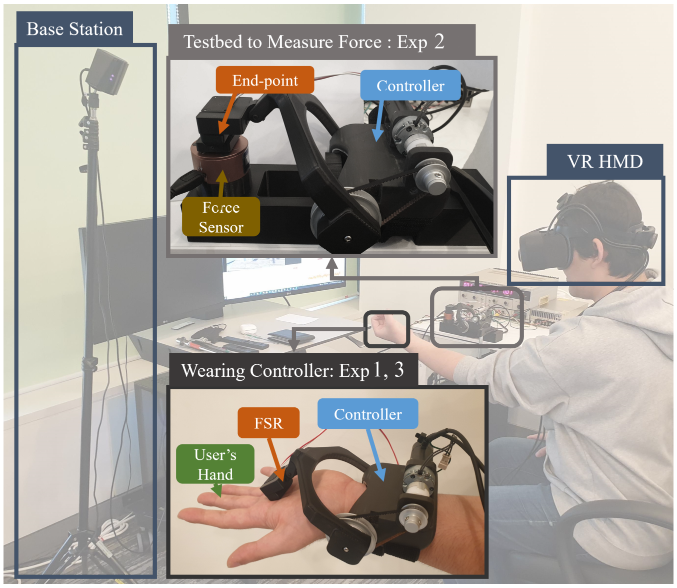

Fig. 4. The setup for experiment and evaluation. For the experiment, we devise our prototype with a torque sensor to measure the force without a user. For the evaluation, the user wears the controller and provides a response to feedback stimuli.

B. *Experiment 2: Rendering Physical Properties*

We aim to build the controller that creates the force according to the given physical properties of a virtual object or environment. In this experiment, we verify whether our prototype could create a desirable level of force according to the given target force computed from the VR scene.

Setup: We used the force sensor (SINGLETACT, CS8-10N) to acquire precise force measurements to verify the haptic rendering performance. As shown in Figure 4, we devised a mechanical fixture to firmly place the prototype rather than equipping it with a subject for accurate measurement. We tested various physical properties with designated VR scenes (Figure 6) by capturing hand motion properties of users like displacement, velocity, and acceleration through VR HMD without wearing the prototype. We conducted an experiment in three unity scenes to measure the performance of rendering the physical properties. First, for the inertia scene, we tested each light, medium, and heavy dumbbell with the gravitational acceleration of 9.8 m/s^2. Second, for the elasticity scene, we measured the rendering performance with three different types of spring (3.5, 7, and 10.5 N/m). We set the maximum spring displacement as 0.1 m. Lastly, we measured the performance of viscosity with three types of wind resistance (0.35. 0.7, and 1.0 Ns/m).

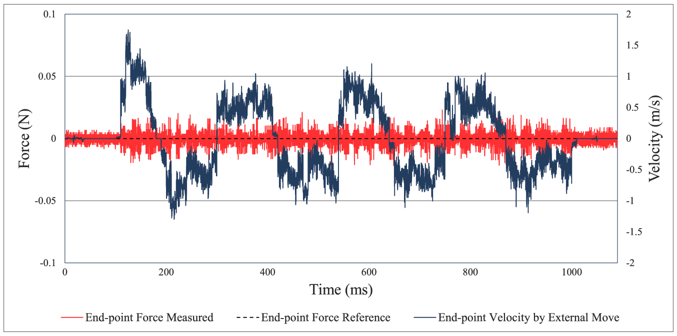

Fig. 5. Our system shows noise less than 0.02 N for keeping 0 N state when the external movement of 1.2 m/s is applied.

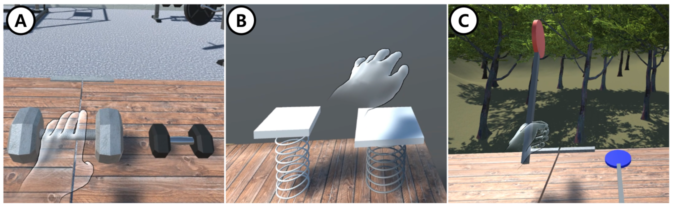

Fig. 6. VR scenes showing various physical properties scenarios including (A) inertia by lifting dumbbells, (B) elasticity by pressing springs, and (C) viscosity by swinging the paddles.

Result: Figure 7 shows the results of our device's rendering performance. Figure 7(A), Figure 7(B), Figure 7(C), each corresponds to the results of Inertia, Elasticity, Viscosity Scene. All the scene shows that our prototype rendered a physical property within 6% error. This means that while using our prototype and constantly interacting with virtual objects, the user can feel the force within that error rate. For all results, we observed the dead band for each curve (0.2 N) which could be due to friction of mechanical structure, gear backlash, and motor hysteresis.

V. PERCEPTUAL THRESHOLD EVALUATIONS

As a haptic device, it is crucial to understand the impact of the proposed feedback on user perception. We explored fundamental user perception elements including the minimum and difference thresholds. Here, the minimum threshold refers to the minimal stimulation that users start to recognize, and the different threshold denotes the resolution necessary to distinguish one stimulus from another.

Previously, researchers employed a psychophysics framework to find out the perceptual performance of users [32], [33]. In this study, we employed a quantitative measure like Just-noticeable Difference (JND) which represents the smallest change in the stimulus intensity that creates a change in the perception of that stimulus [34], [35]. To be specific, we employ a 3-down, 1-up staircase method to measure JND with a small number of trials with high accuracy [36]. We recruited 10 participants with a mean age of 27.5. All participants were right-handed and wore the wrist-mounted haptic controller as shown in Figure 4. Figure 8 is an example of the process of our perceptual threshold evaluations.

A. *Minimum Force Feedback Threshold*

Setup: We excluded extremely low or high values as starting stimuli, so we can focus on the appropriate force range to reduce the number of trials. 10 participants started at 0.65 N for force feedback. We used 0.19 N as the first step size and 0.13 N for the second and third step sizes. Afterward, the

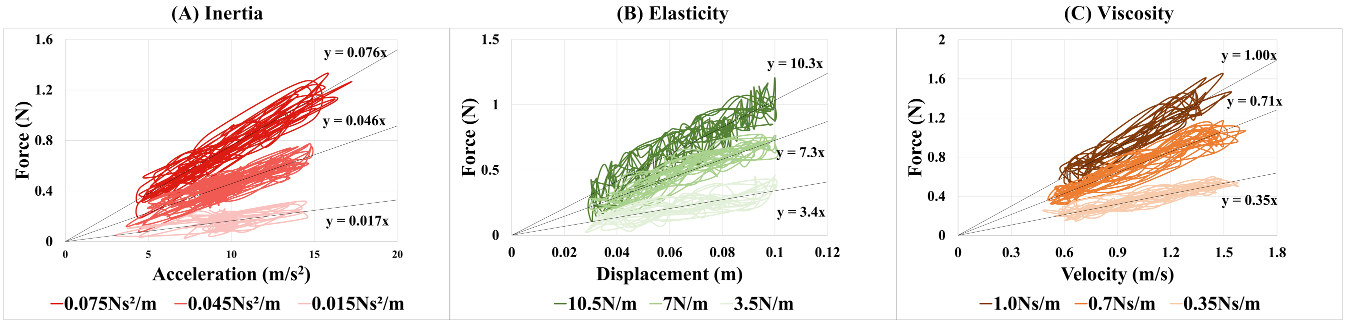

Fig. 7. To obtain the results of rendering performance, force graphs against hand movement (acceleration, displacement, velocity) are drawn. Each force feedback is generated in proportion to the desired physical properties (inertia, elasticity, and viscosity) where the gradient of each line represents system performance.

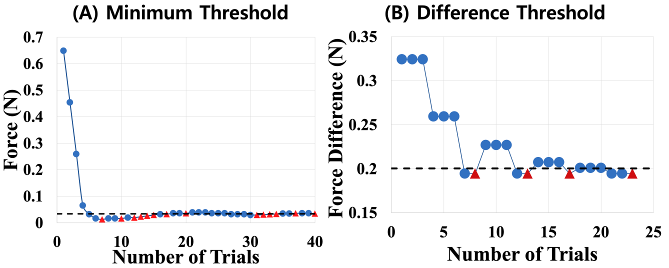

Fig. 8. An example (P3) of a staircase in the three-down, one-up method. Here, the observed (A) minimum threshold is 0.0335 N and (B) difference threshold is 0.2 N.

step size was reduced by half. The threshold was computed by averaging the last 10 reversals from each ladder.

Result: For all 10 participants, the average minimum threshold came out to be 0.114 N (SD=0.155). It took about 45 trials to reach the result after 10 reversals. This result means that users are hard to recognize when a force less than 0.114 N is applied to the palm.

B. Difference Threshold for Force Feedback on Palm

Setup: 10 Participants responded whether they perceived the difference of force-feedback or not, as compared to the previous value that the device pressed on the palm. If it can be distinguished from previous stimuli, they answered “Yes”, otherwise they answered “No”. For starting force, we chose 1.3 N which can be easily felt by all participants while providing enough room to test the difference threshold. For the initial step size, we chose 0.32 N which clearly provided perceptual difference found heuristically with few users. The overall force range was between 0.3∼1.5 N.

Result: For all 10 participants, the average difference threshold value was 0.248 N (SD=0.121). It took about 30 trials to reach the result. This means that when designers show the two objects to users, the physical properties of each object have to differ at least 0.248 N to feel the difference with our device.

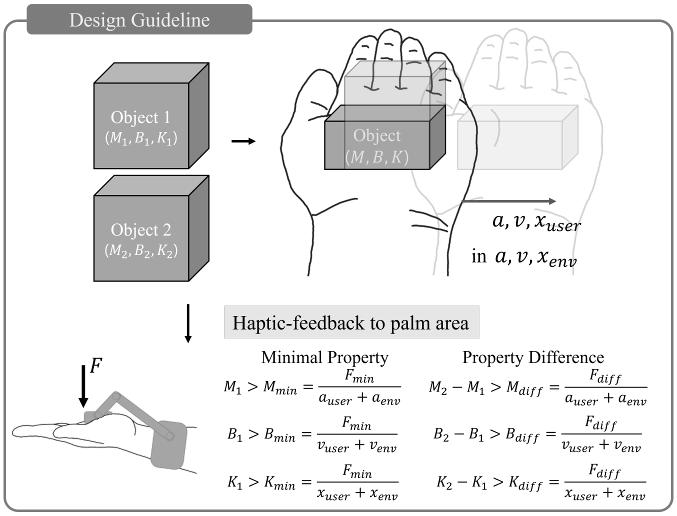

Fig. 9. In a VR environment $(a_{env}, v_{env}, x_{env})$ the physical properties of any two objects $(M,\ B,\ K)$ are specified based on the minimum, difference threshold of the force feedback (F_{min}, F_{diff}) while reflecting dynamic hand movement $(a_{uesr}, v_{user}, x_{user})$.

VI. DISCUSSION

Haptic sensations should be given when interacting with the VR environment. To this end, we focus on not interfering with the hand motion when the device is not in operation. Furthermore, we carried out a zero-force control experiment while allowing free hand movement. The average exerted force to the hand upon movement of the hand is 0.02 N, which would hardly affect the movement of the hand.

One of our main ideas was to transform the physical value computed from the VR environment to generate the force from the proposed prototype. Figure 7 shows the physical values corresponding to each repeated change in the acceleration, position, and velocity of the hand. From these results, Force rendering according to the user’s hand movement shows that our device rendering performance has less than 6% error comparing the FSR values and Unity scene setup value. These results verify that the proposed prototype transmits the desired value computed from the VR scene. This also tells that our system supports dynamic hand movement when exerting desired force feedback.

Based on our results on perceptual evaluation, we suggest design guidelines for building a VR experience with the proposed prototype. The perceivable minimum force was 0.114 N and the minimum force resolution was 0.248 N from our evaluation. In summary, we would recommend users enter physical parameter values to the virtual objects based on Eq.5 and Eq.6 which are further explained in Figure 9.

$$F_{obj_1}, F_{obj_2} > F_{min} = M_{min}a + B_{min}v + K_{min}x \tag{5}$$

$$|F_{obj_1} - F_{obj_2}| > F_{diff} = M_{diff}a + B_{diff}v + K_{diff}x \tag{6}$$

VII. Limitations and Future work

Although our prototypes can provide users with free hand motion and also precise force feedback, it has some limitations. First, it can only provide one direction of force feedback. Devices push the palm in one direction to render force feedback. So it would be hard to apply our devices in some situations. Second, the weight of our devices is 386 g, which is quite heavy for a wrist so users can be tired after a long time of use. In future work, we can vary the structure of the end effector to render more immersive feedback or bidirectional force feedback.

VIII. Conclusion

In this paper, we designed a wrist-mounted haptic controller rendering precise physical properties to the user. From the results of the physical property rendering experiment, the proposed controller forms desired inertial, viscosity, and elasticity. Here, we enable the users to interact organically with the virtual environment by adding haptic feedback in accordance with inertia, elasticity, and viscosity. In terms of force feedback-based controller configuration, we come up with a virtual environment criterion based on the minimum and the difference threshold values. Based on the virtual environment haptic feedback criteria above, we provide an in-depth basis for the design guidelines through experiments to determine whether the user would actually perceive the intended sensation.

Acknowledgment

This work was supported by the National Research Council of Science & Technology (NST) grant by the Korea government (MSIT) (No. CRC21011) and the National Research Foundation of Korea(NRF) grant funded by the Korea government(MSIT) (No. 2022R1A4A5033689). We thank Mike Sinclair and Michel Pahud for their assistance.

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