MoveVR: Enabling Multiform Force Feedback in Virtual Reality using Household Cleaning Robot

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ABSTRACT

Haptic feedback can significantly enhance the realism and immersiveness of virtual reality (VR) systems. In this paper, we propose *MoveVR*, a technique that enables realistic, multiform force feedback in VR leveraging commonplace cleaning robots. *MoveVR* can generate tension, resistance, impact and material rigidity force feedback with multiple levels of force intensity and directions. This is achieved by changing the robot's moving speed, rotation, position as well as the carried proxies. We demonstrate the feasibility and effectiveness of *MoveVR* through interactive VR gaming. In our quantitative and qualitative evaluation studies, participants found that *MoveVR* provides more realistic and enjoyable user experience when compared to commercially available haptic solutions such as vibrotactile haptic systems.

Author Keywords

Force feedback, haptic feedback, virtual reality, VR, robotics, cleaning robot, human-robot interaction.

CCS Concepts

•**Human-centered computing** → **Human computer interaction (HCI); Virtual reality; Haptic devices;** *Interaction devices;* •**Hardware** → *Haptic devices;*

INTRODUCTION

The advancements in head-mounted 3D displays, tracking, and interactive technologies have brought increasingly realistic virtual reality (VR) experiences to consumer-affordable devices. Although commercial VR can render realistic 3D scenes with spatial audio, it struggles to deliver compelling force haptic experiences, which are indispensable to realistic and immersive VR experiences.

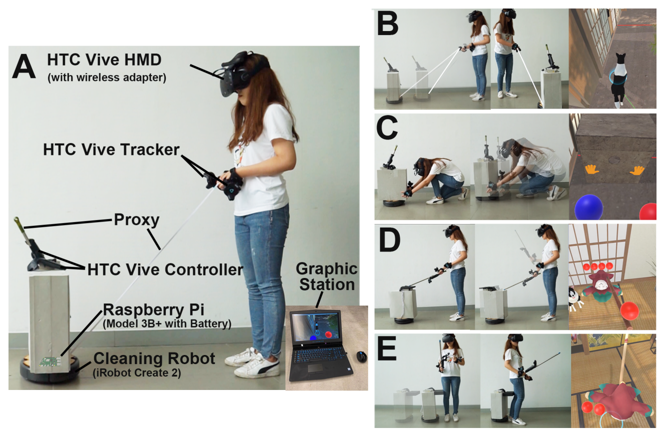

Figure 1. Overview of *MoveVR*. A: Hardware setup. B: Adjusting tension intensities and directions by configuring the relative position between the robot and the user. C: Multi-level resistance force feedback by configuring the robot's direction of motion. D: Simulating material rigidity through rotating different material proxies within reach of users. E: Applying different levels of impact force to users by varying the speed.

Researchers have spent a significant amount of effort in designing various types of robotic force feedback instruments for VR, such as hand-held controllers [11, 14, 33, 38], wearable devices [10, 24, 26, 34, 35], and other grounded robotic solutions [2, 6, 20]. However, these solutions can only provide local feedback on a single finger or body part, and rely on highly customized hardware that is challenging to replicate and scale outside the research lab. Recently, commercially available robots have been utilized to provide force feedback [3, 4, 5, 13, 25]. However, existing drone-based solutions can only provide low-fidelity force feedback with very limited intensity [4] due to their under-actuated nature.

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With millions of cleaning robots shipped into everyday households every year [31], we believe there are great opportunities leveraging these domestic robots to conduct tasks beyond just household cleaning. In this paper, we present *MoveVR*, a new technique utilizing household cleaning robots to provide multiform force feedback for immersive VR experiences. *MoveVR* generates pulling, pushing, resisting, and material rigidity sensations with multiple levels of force expressions by changing the robot's moving speed, position, as well as the carried proxies. To evaluate our solution, we first observed users' ability to distinguish among multiple levels of force intensity, direction and material rigidity in a force perception study. Based on the results, we further compared *MoveVR* with no-haptic control group and existing solutions with vibrotactile haptic, and passive haptic feedback to better understand the user's preference. Results indicate that *MoveVR* can render more realistic and enjoyable VR experiences while having the advantage of easy scalability and versatility in supporting various types of VR scenarios. Finally, we conclude with discussions and limitations that need to be addressed in future work. Our contributions are as follow:

1. For the first time, *MoveVR* enables multiform force feedback using a common household cleaning robot. We present the *MoveVR* prototype with easy fabrication and assembly methods using everyday materials, objects and tools.

2. Our force perception study demonstrates that *MoveVR* can enable rich force expressions (tension, resistance, impact and reaction) with multiple levels of force intensity, force direction, and material rigidity.

3. Our user experience study shows that *MoveVR* provides a more realistic and enjoyable VR experience when compared to commercially available haptic solutions.

RELATED WORK

Force (kinesthetic) feedback mainly relies on sensory cells in our muscles, tendons, and ligaments of our musculoskeletal system. Thus, the hardware delivering the feedback must be capable of producing much larger movements and forces compared to cutaneous devices [28]. Force feedback provides sensations such as an object's rigidness, weight or reaction force, etc. [8] In this section, we give a brief overview of existing robotic haptic feedback solutions, their use scenarios, and their limitations. We then dive deeper to discuss the difference between *MoveVR* and existing robot-based encountered-type force feedback solutions to better position our work.

Hand-held robotic force feedback solutions use DC motors or brakes to create sensations such as weight shifting [29, 38], reaction force [32, 33], resistance force [11], and impact force [14]. Researchers also explored gyroscopic effects to create different types of realistic force feedback [7, 18, 36]. However, these hand-held solutions constrain free-hand grasping interaction with virtual objects. To enable free-hand force feedback, grounded solutions were explored including pen-based force feedback devices [1, 2, 20] or other force display devices [21, 22]. However, grounded solutions are constrained to a fixed position, which limits the interactive space. Therefore, researchers explored robotic body-grounded wearable solutions by applying force to users' fingers [9, 10], wrist [15, 23, 26], forearm [34, 35], or other body parts [12, 19, 24]. All these solutions can only provide local feedback on a single finger or a specific body part. Furthermore, the size of the hardware tends to be proportional to the force it actuates. These solutions are challenging to replicate and scale outside the research lab.

Sharing a similar concept with our *MoveVR* approach, "Robotic Graphics" proposed by William A. Mcneely illustrates the concept of "robots simulating the feel of an object and graphics displays simulating its appearance" [25]. This is commonly achieved by encountered-type haptic devices following the motion pattern of the virtual object to generate realistic physical sensations for VR users. This has opened new opportunities for enhancing force feedback in virtual reality.

Encountered-type haptic solutions using the robotic arm [6, 37] relies on a robotic arm to render real, physical objects with expressions of texture, shape, touch, airflow as well as temperature. *ShapeShift* [30] enables dynamic 2D spatial manipulation with a mobile tabletop shape display. However, these conventional encountered-type devices are fixed in the environment, resulting in feedback possible only in a very limited space. To enable haptic feedback in an open space, He et al. [16, 17] proposed and implemented desktop robotic haptic proxies using wheeled robots that configure physical objects for encountered-type haptic feedback. Other researchers explored new haptic interfaces in virtual reality using quadcopters rendering force feedback [3, 4, 5, 13]. Although drone-based haptic solutions allow haptic interaction in 3D space, they only provide a limited amount of low fidelity vertical force feedback [4] and unable to provide sufficient lateral force feedback due to their under-actuated nature.

In contrast with all the solutions above, *MoveVR* is unique as it investigated the usability and functionality of the commonplace cleaning robots as a more accessible haptic display solution. We believe studying cleaning robot is of particular interest due to its ubiquity in the household [31]. Techniques we explored could also apply to other motorized platforms such as remote control toy cars. While consumer drones are good at generating vertical force feedback, *MoveVR* is good at simulating lateral force feedback. We believe *MoveVR* is complementary to drone-based solutions for 3D force feedback.

MOVEVR IMPLEMENTATION

In this section, we discuss the *MoveVR* system, including its hardware and software, as well as the accessory fabrication approaches using everyday materials and objects.

Hardware

MoveVR has four major hardware components: a cleaning robot, a robot motion controller (RMC), a head-mounted VR display (HMD) with a location tracking system, and a graphic station. In our prototype, we used *iRobot Create 2* [1], an HTC

[1] https://www.irobot.com/about-irobot/stem/create-2

Vive Pro VR system with two HTC Vive trackers. The RMC is a Raspberry Pi (Model 3B+) with ROS running on Linux, which controls the robot through a USB dongle. A 5V battery bank powers the Raspberry Pi. The graphic station is an Alienware 17 R5 laptop with an Intel i9-8950HK (2.9GHz, 6 cores) CPU, 32GB RAM, 8 GB RAM and GeForce GTX 1080 Graphics Card. A WiFi router is used to build a LAN for the RMC and the graphic station to communicate. Furthermore, we used a wireless VR headset adapter for users to move freely. A noise-canceling headphone was used to filter out environmental and robot noises. Figure 1 shows the setup of our prototype. To track the positions and directions of the user, the robot and proxies, we attached two trackers on user's two hands, one controller on the robot and the other one on the optional user-driving proxy.

Software

MoveVR provides force feedback to users by controlling the cleaning robot to move along a specific path with a certain speed or rotate a particular angle. To achieve this purpose, we designed *MoveVR*'s software architecture as illustrated in Figure 2. We implemented a control script using the iRobot's Create ROS driver [2], and a server with socket protocol, both of which run on the RMC. The Python script translates the control commands sent from the graphic station and controls the movement of the robot through a USB dongle. The computing logic unit running on the graphic station makes decisions and sends control commands via the robot control unit under different scenarios based on collected position information and robot sensor information. We rendered VR content using Unity3D and displayed it on the HMD via Stream VR.

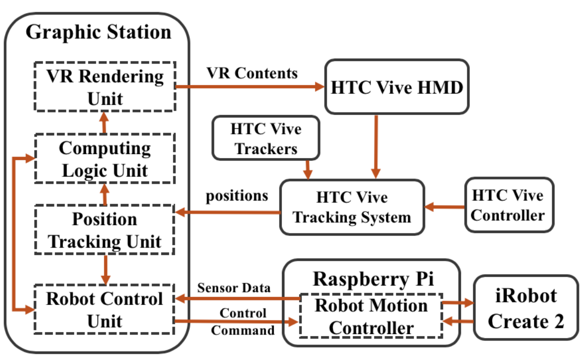

Figure 2. MoveVR system architecture.

We obtained the agent's position/orientation by tracking the attached HTC Vive controller. Firstly, we program the robot to move forward for a distance (1m in our case) and observe that vector in Vive's coordinate system. The relative displacement will be the robot's forward direction. This allows us to convert vectors between the 2 coordinate systems easily. Then we rendered the VR object to the controller on top of the proxy and coordinated its size, position, and orientation based on the calculated orientation and position. To handle irregular surfaces, a proportional integral derivative (PID) control method is implemented as Algorithm 1 shows. This algorithm enables the robot to move to the destination location quickly and precisely.

[2]http://wiki.ros.org/create_autonomy/

Algorithm 1 Movement Control Algorithm

function ROBOTMOVEMENT($\overrightarrow{DesPos}$,$\overrightarrow{CurPos}$,$CurDir$)
  $d \leftarrow \|\overrightarrow{DesPos} - \overrightarrow{CurPos}\|$
  while $d > D$ **do** ▷ D is the nearness threshold
    $a \leftarrow getAngle(\overrightarrow{DesPos}, \overrightarrow{CurPos}) - CurDir$
    if $|a| > A$ **then** ▷ A is the angle offset threshold
      $rotate(a)$ ▷ Rotate the robot a degrees
    end if
    $d_1 \leftarrow getNextMove(d)$
    $forward(d_1)$ ▷ Forward the robot d_1 meters
    $\overrightarrow{CurPos} \leftarrow getCurPos()$ ▷ Get current position
    $d \leftarrow \|\overrightarrow{DesPos} - \overrightarrow{CurPos}\|$
  end while
end function

Fabrication and Assembly

The cleaning robot is used as our force feedback actuator and also serves as a platform to carry physical objects providing encountered-type force haptic. These objects used for interaction will be referred to as proxies in later sections of this paper. Here we define three kinds of proxies 1) **carry-on proxy** that is carried by the robot; 2) **user-driven proxy** that is held by the user alone; 3) **shared proxy** that links the robot and the user.

To make *MoveVR* relatable to users, we identified a few everyday objects serving as proxies (shown in Figure 3 B). To assemble the carry-on proxy onto the cleaning robot, we identified a few fabrication tools (shown in Figure 3 A and 3 C). We proposed and demonstrated three manual assembly methods listed below.

1) **Tying the shared proxy to the robot.** As Figure 3 D shows, users can tie shared proxies (strings, ropes or sewing threads) to the robot to simulate force feedback such as tension.

2) **Attaching the carry-on proxy on top of the robot using adhesive materials.** Through placing pairs of touch fasteners on the carry-on proxy and the robot, users can easily and steadily attach the add-ons as Figure 3 E indicates. Another approach is to tape the add-ons onto the robot directly as Figure 3 F shows. To track the position of the robot, users need to fix a VR controller onto the proxy as Figure 3 H shows.

3) **Fabricating the hand-held user-driving proxy.** As Figure 3 I shows, users can attach the VR controller with tape onto a user-driving proxy simulating a stick or a fishing rod. The proxy can be a wooden or paper-rolled stick, which can be inserted into the carry-on proxy providing free-hand grasping as Figure 3 J shows.

Since these assembly materials are easily removable, they will not damage the robot. We believe that each application may have different assembly requirements. Therefore, developers can provide users with simple assembly instructions along with the applications. End-users can follow the instructions and use everyday household objects to fabricate *MoveVR*.

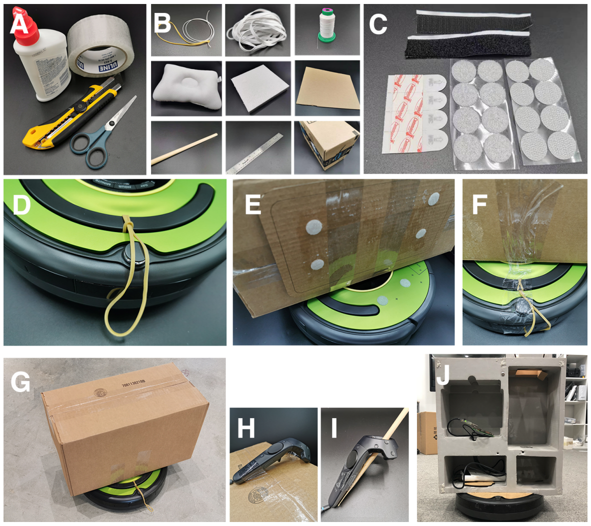

Figure 3. Fabricating and assembling MoveVR. A: Example of fabrication tools. B: Example of everyday objects as proxies. C: Touch fasteners or double-sided tape to fix the carry-on proxy. D: Attaching the shared-proxy onto the robot. E: Fixing the carry-on proxy using touch fasteners. F: Fixing the carry-on proxy using tapes. H - I: Attaching the VR controller with the user-driving proxy. G/J: Examples of MoveVR carrying proxies.

MOVEVR FORCE EXPRESSIONS

MoveVR can provide a variety of force feedback with multiple degrees of force intensity and direction. Below we describe four force expressions that *MoveVR* can create. To test the system's force capacity, we used a force meter (100N load capacity, 0.1N resolution) that can measure the peak force strength for a given time period or force values in real-time.

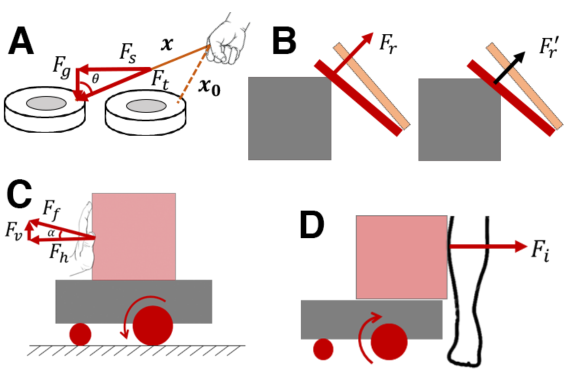

Figure 4. Force expression explanation. A: Tension force through an elastic string. B: Reaction force simulating material rigidity. C: Resistance force against user's force. D: Impact force that the robot actively applies to the user.

Tension Force Feedback

MoveVR can create continuously changing tension with an elastic string between the user and the robot as a shared proxy. As Figure 4A shows, different levels of tensile strength can be simulated through changing the distance between the user and *MoveVR*: the further they are apart, the stronger the tension. We use Hooke's law (shown in Equation 1) to model this relationship. x and x_0 represent the stretched length and the initial length of the elastic string respectively. k represents the Young's modulus of the elastic string ($k = 12.5N/m$ for the elastic string in Figure 3 D).

$$F_t = k(x - x_0),\, x > x_0 \tag{1}$$

For a given type of elastic string and a certain surface that *MoveVR* operates on, there is a maximum tension force that the robot could apply to a human. Exploring this variable would help us understand the limit of our design space. The maximum tension force is relevant to the friction to the robot that can be expressed as follows: $F_s = F_t sin\theta \leq F_s{}^{max} = \mu N$ where μ represents the coefficient of three types of friction: 1) **static friction** where $\mu = \mu_s$ which is the coefficient of static friction, 2) **sliding friction** where $\mu = \mu_k$ which is the coefficient of sliding friction, and 3) **rolling friction** where $\mu = \mu_r = \frac{b}{R}$. b is the coefficient of rolling friction and R is the radius of the wheel in meters. $N = mg - F_g = mg - F_t cos\theta$ represents the normal force as Figure 4A shows. Based on these two equations, we can obtain $F_t{}^{max}$ shown in equation 2. μ represents the coefficient of static friction. m represents the mass of the robot. θ represents the angle between the string and perpendicular to the ground (pitch angle).

$$F_t{}^{max} = \frac{\mu mg}{sin\theta + \mu cos\theta} \tag{2}$$

The maximum tension force limits the range of pitch angles *MoveVR* can support. Here we present the method calculating the maximum tension intensity and pitch angle. Firstly, we measured the coefficient of static friction - μ, which is relevant to surface materials. This is achieved by measuring the peak force value using the force meter pulling the robot horizontally until it moved. We repeated this procedure 12 times on each of the following three household surfaces: wooden floor, concrete floor and carpet. Results show that the static friction averages 12.8N (SD = 0.59N) on a wooden floor, 13.0N (SD = 0.45N) on a concrete floor, and 15.5N (SD = 0.42N) on a carpet when the robot's wheel motors are activated. We then calculated μ of each surface that are 0.373 (wooden), 0.379 (concrete) and 0.452 (carpet). Finally, we obtain $F_t{}^{max}$ along with the maximum pitch angle by solving Equation 1 and 2. For instance, assuming that the user's hand is 1-meter above the ground and Young's modulus of a 1-meter-long elastic string is 10, we can calculate the maximum tension strengths - $F_t{}^{max}$ (maximum pitch angles - θ^{max}) to be 9.3N (58.8°) on a wooden floor, 9.5N (59.1°) on a concrete floor and 11.5N (62.3°) on a carpet.

MoveVR can either provide different levels of tension or supply a sense of direction via the tensile force by changing the robot's relative location to the user. By programming the movement pattern of the cleaning robot, utilizing its ability to generate constant and varying levels of tension, as well as the direction of this force, *MoveVR* can create patterned tension force feedback.

Two examples are shown in Figure 5 A. The first example shows the simulation of a fishing activity where users hold a rod attached to *MoveVR*. The sensation of the fish fighting against the line is simulated by *MoveVR* using patterned

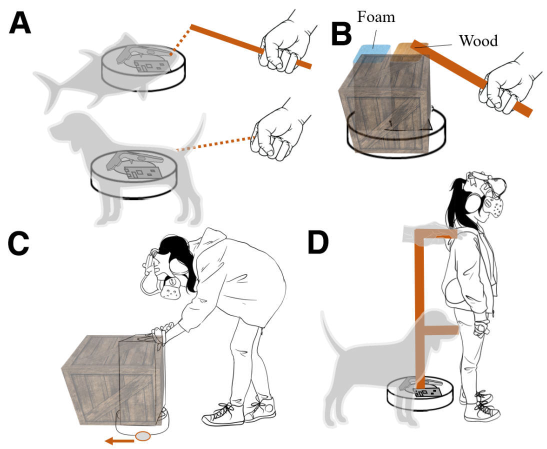

Figure 5. ***MoveVR*** **can simulate a variety of force feedback with everyday objects as proxies. A: Tension using string/rope proxies between users and robots. B: Reaction with proxies built by different materials. C: Resistance by configuring the wheels' status. D: Impact from the robot crashing on users with varying speeds.**

tension force feedback. The second example simulates a virtual dog guiding the user by providing continuous pulling feedback via a leash. *MoveVR* can guide the user to follow a specific path.

Resistance Force Feedback

MoveVR can resist the user's force through friction by configuring the robot's active status or direction of motion. The friction can be simply modeled by equation 3 where mg represents the gravity of the robot and α represents the angle between the push force and the lateral direction. We use same friction coefficients presented in subsection *Tension Force Feedback* to model the resistance force as equation 3.

$$F_f = \frac{\mu mg}{cos\alpha - \mu sin\alpha} \quad (3)$$

We designed three resistance force levels as follows. 1) **Concrete resistance**. The user cannot push *MoveVR* forward; the robot is locked in place with its wheels perpendicular to the direction of the user's push. 2) **Heavy resistance.** The user pushes an activated *MoveVR* until the robot's wheels slide. 3) **Light resistance.** The user pushes an inactivated *MoveVR* until its wheels roll. Using these expressions, *MoveVR* can simulate virtual boxes with different weights by configuring the cleaning robot as Figure 5 C illustrates. We carefully design the VR game so that robots move to a specific location and stay there as a static object to provide passive force feedback. The robot will move to the next position after the user finished interacting with the current virtual object, which can be detected by the motions of trackers on the hands and controllers on the proxies.

We repeatedly measured the resistance by pushing the robot horizontally using a force meter on three household surfaces: concrete, wooden, and carpet. We measured 12 times for each condition and obtained the results in Table 1.

Table 1. Resistance force intensity under different configurations on three common surface grounds. X(Y) in each cell indicates average value (standard deviation value).

Type	Concrete	Heavy	Light
Wooden	$28.34(0.55)N$	$12.30(0.59)N$	$4.96(0.28)N$
Concrete	$31.73(0.52)N$	$12.82(0.52)N$	$5.77(0.29)N$
Carpet	$58.98(0.75)N$	$15.20(0.52)N$	$8.68(0.28)N$

Impact Force Feedback

MoveVR can actively apply impact force on users simulating the action of attacking, crashing, touching, etc. The robot can be programmed to make contact with the user using a carry-on proxy as Figure 5 D illustrates. We model the impact force - F_i in a deformation equals to the work done by a spring force - and can be expressed as equation 4. *MoveVR* simulates varying impact force strength by programming the robot's moving speed - v since the deformation slow-down distance (s) and the robot weight (m) are nearly constant.

$$F_i = \frac{m \times v^2}{s} \quad (4)$$

We measured the actual speed of the robot at a maximum speed of around $435mm/s$ and a minimum speed of around $44mm/s$. If we assume $s = 0.01m$, then the maximum impact force on the user is $66.2N$.

As Figure 5 D illustrates, the robot bumps into the user to simulate a dog rubbing up against his/her leg or a strike on his/her shoulder. *MoveVR* can create different amounts of impact on users by programming the speed of the cleaning robot encountering the user.

Material Rigidity Force Feedback

We enable a special kind of force feedback simulating materials with different rigidity. In VR gaming, there are many scenarios where players do not directly make contact with VR characters but rather make indirect contact by holding physical proxies (Figure 5 B). In these situations, we attach carry-on proxies of different materials on top of the cleaning robot. When users are contacting virtual characters via a user-driving proxy, the robot rotates the corresponding material to simulate different rigidity when the proxy is hitting the material. Users can feel the material rigidity through the reaction force on users' hands. We model the reaction force - $F_r(t)$ slowing down the user-driven proxy in a deformation equal to the momentum of a spring force - and can be expressed as equation 5. m and $V(t)$ represent the effective mass and the effective speed of the user-driving proxy. $\Delta t = t_2 - t_1$ represents the collision time. The proxy encountering onto *MoveVR* bounces in different patterns on different materials. To provide different reaction force feedback simulating rigidity, we can modify the proxy material to change the collision time, bouncing pattern, and vibrotactile feedback from the carry-on proxy.

$$\int_{t_1}^{t_2} F_r(t)dt = m \times V(t_1) - m \times V(t_2) \quad (5)$$

The example in Figure 5 B simulates two virtual objects built with different materials. *MoveVR* can provide users with material rigidity sensations of hitting different objects via physical proxies. This is achieved by controlling the robot to rotate to a certain angle placing different material proxies within reach of users.

Opposite from reaction force feedback, *MoveVR* can also purposefully avoid contact with the user. We refer to this type of interaction as evasive force feedback. We consider this to be unique as the strong contrast between hitting an object in the real world and a missing hit. We demonstrated one example shown in Figure 9 B where an enemy escapes from the user's hit.

USER STUDY 1: FORCE PERCEPTION STUDY

In this section, we discuss a group of user studies we conducted, exploring *MoveVR*'s ability to provide multiple levels of distinguishable force intensity and directions.

Tension Force Intensity

Attaching a 1-meter-long elastic string between the robot and the user, we designed four levels of tension: zero-level (L0, loose elastic string, $0N$), low-level (L1, 1.2-meter-long $1.9N$), medium-level (L2, 1.4-meter-long $4.0N$), and high-level (L3, 1.7-meter-long $7.0N$).

Tension Force Direction

Connecting a stretched 1.4-meter-long (originally 1-meter-long) elastic string with a force intensity of approximately $4N$ between the robot and the user, we tested five force directions by programming the robot to move to different locations around the user. If the user takes the central point of a map with the top edge representing North, then forces are from the West (L), Northwest (45°, FL), North (F), Northeast (135°, FR) and East (R).

Resistance Force Intensity

We used the three levels of resistance force in subsection *Resistance Force Feedback* for a box pushing scenario simulating different weights of a virtual box: 1) Light weight (L1): we deactivated the robot so that users can push the robot forward easily. 2) Medium level weight (L2): we activated the robot that users need to push harder to move the robot forward. 3) Heavy weight (L3): the robot is placed with wheels perpendicular to the direction of the user's push, which requires the user to exert significantly more force.

Material Rigidity through Reaction Force

We designed five types of reaction force to simulate evasive force and different material rigidity in a hitting scenario as shown in Figure 5B. The robot was programmed to rotate, exposing the following materials to the users: A pillow (L1), foam packaging (L2), a cardboard box (L3) and a plastic box (L4). The robot can also avoid user's hit by moving backward for 1 meter (L0).

Impact Force Intensity

When the robot runs into the user at different speeds, it provides various levels of impact force to the user. We designed three levels of impact including light impact force simulating a soft touch (L1, $50mm/s$), medium level impact simulating a punch (L2, $200mm/s$), and heavy impact force simulating a crash (L3, $400mm/s$).

Participant and Procedure

We recruited 12 participants with an average age of 23.4 (SD = 3.29, 4 females) for our study evaluations. We first explained the purpose of this study. Then, we asked the participant to wear a HTC Vive HMD with a black screen so that she/he would focus solely on the haptic sensation.

Each force study was broken into 2 rounds, the practice round and the experimentation round. In the practice round, we exposed the user to several different force conditions. Each study has a minimum of 3 different force conditions and a maximum of 5 conditions. For each condition, we gave the user a corresponding number (1 for least intense and 5 for most intense), which they will associate with the force they were experiencing. Once the user got familiar with each force condition, we entered the experimentation round, where each participant experienced force feedback at a randomly generated sequence of levels through autonomously moving/rotating the robot to the programmed position. The experimenter asked the participant the corresponding number of each condition, recorded the result manually and compared with the ground truth. In total, each subject participated in $4\ sessions \times (4+5+3+5+3)\ conditions = 80\ trials$. The experiment took about 30 minutes per user. Users were compensated 15 USD for their participation.

Results

Figure 6 shows the accuracy and confusion matrix of each benchmark study. Results indicate that *MoveVR* can provide multiform multiple levels of force feedback that users can recognize accurately.

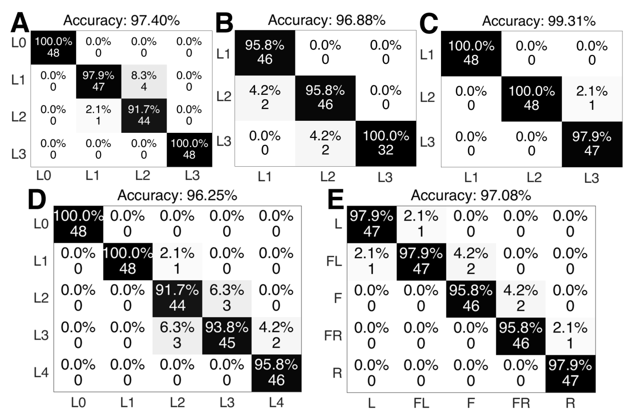

Figure 6. Results of force perception accuracy. A: Tension force intensity. B: Resistive force intensity. C: Impact force intensity. D: Material rigidity. E: Tension force direction.

Overall, users correctly identified *MoveVR*'s force feedback at the following rates: 97.4% accuracy for four tension force intensities (Figure 6 A), 96.9% accuracy among three resistance force intensities (Figure 6 B), 99.3% accuracy among three impact force intensities (Figure 6 C), 97.1% accuracy among five material rigidities (Figure 6 D), and 96.3% accuracy among five tension force directions (Figure 6 E). Note that errors in our study could be a result of fading memory between sessions. Even so, our participants performed well in matching the force condition they experienced in the experimentation round to the ones they were exposed to the practice round. Results show that they could indeed differentiate the multiple levels of force feedback for each force category.

USER STUDY 2: USER EXPERIENCE STUDY

To evaluate *MoveVR*'s ability to provide realistic and enjoyable VR experiences, we conducted a user experience study in which participants experienced three VR scenarios comparing *MoveVR* with three other haptic feedback methods. In this section, we walk through the experiment design and present the results and findings.

We evaluated four haptic conditions including: 1) ***barehand*** condition where the user wears HTC Vive trackers on his/her hands with no haptic feedback; 2) ***vibrotactile haptic***, that uses HTC Vive controllers providing vibration feedback; 3) ***passive haptic***, in which we placed physical props in positions correlated to graphics in a VR application; 4) ***MoveVR***.

Experiment Design Walk-through

Our demo experience is a VR game where the user returns home after walking her/his dog, finding that the door is opened with its entryway blocked by a box. The user must move the box out of the way to get into the house where she/he will find a stranger (enemy) trying to attack her/him. The user needs to pick up a stick to hit and defeat the enemy.

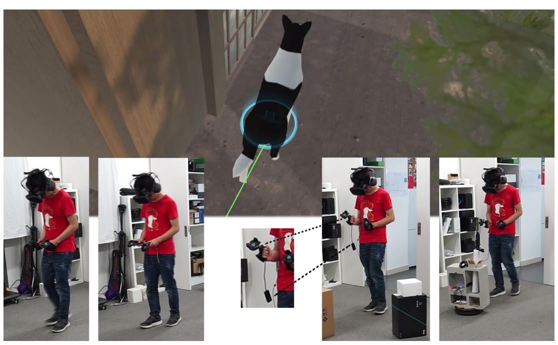

Figure 7. Dog walking VR scenario with four haptic conditions.

Dog Walking Scenario

As shown in Figure 7, the user has a joint experience with a dog leading her/him to the front door. In the ***barehand*** condition, the user sees the dog walking at a certain distance away from the user with no haptic feedback. In the ***vibrotactile haptic*** condition, the user feels vibrotactile sensation from the controller until he or she arrives at the door with the dog. In the ***passive haptic*** condition, the user feels a weight force from a held leash. In ***MoveVR*** condition, users hold a leash attached to the robot, which exerts a continuous pulling sensation. After the user arrives at the door, he or she is instructed to release the leash.

Box Pushing Scenario

As shown in Figure 8, the user notices a box blocking the entry. He or she needs to push the box away to enter the house. In the ***barehand*** condition, the user pushes a virtual box with no haptic feedback. Under the ***vibrotactile haptic*** condition, the user needs to move the controller close to the box and press the trigger to move the box away with continuous vibration feedback. In the ***passive haptic*** condition, the user needs to push a physical box lying on the ground with a HTC Vive controller attached for real-time virtual box rendering. In ***MoveVR*** condition, the robot moves to where a virtual box is placed and deactivates itself. When the user pushes the carry-on proxy, the robot moves forward.

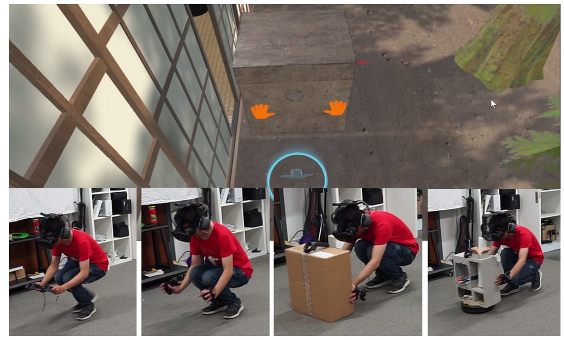

Figure 8. Box Pushing VR scenario with four haptic conditions.

Enemy Hitting Scenario

After the user enters the room, he or she encounters an enemy and a stick in a barrel. The user is instructed to pull out the stick from the barrel and use it to strike the enemy. There are three conditions in which users interact with the enemy: 1) The user successfully hits the enemy (**hit**). 2) The user fails to hit the enemy (**miss**). 3) The enemy attacks the user and the user successfully hits back (**attack**). The enemy appears in a sequence of hit-miss-hit-miss-attack-miss-hit-hit-attack.

In the ***barehand*** condition, users move their hands close to the virtual stick to acquire it and then hit the enemy without additional haptic feedback. In the ***vibrotactile haptic*** condition, users move the controller close to the virtual stick and press the trigger to pick it up. When users hit the enemy in **hit** and **attack** tasks, there is vibrotactile feedback from the controller. Under the ***passive haptic*** condition, we place physical package boxes in the corresponding positions where the virtual enemy is located. When the user hits the enemy, he or she hits the physical box with a real stick. However, there is no haptic feedback for **miss** and **attack** tasks. Using ***MoveVR***, the user picks up a real stick inserted in the carry-on proxy. We programmed the robot to move to the corresponding positions if in **hit** task. The robot will skip positions if in **miss** task. The robot runs into the user in **attack** task with a speed of $200mm/s$. After the enemy appears nine times, it disappears permanently and the barrel reappears. The user is asked to put the stick back. The session is concluded as we physically guide the user out of the lab.

Participants

In this experiment, we recruited 24 users with an average age of 24.2 (SD = 7.6, 9 females). Eight users had no previous VR experience and the rest had experienced VR between 1-3 times previously. The experiment took about 1 hour per user. Users were compensated 20 USD for their participation.

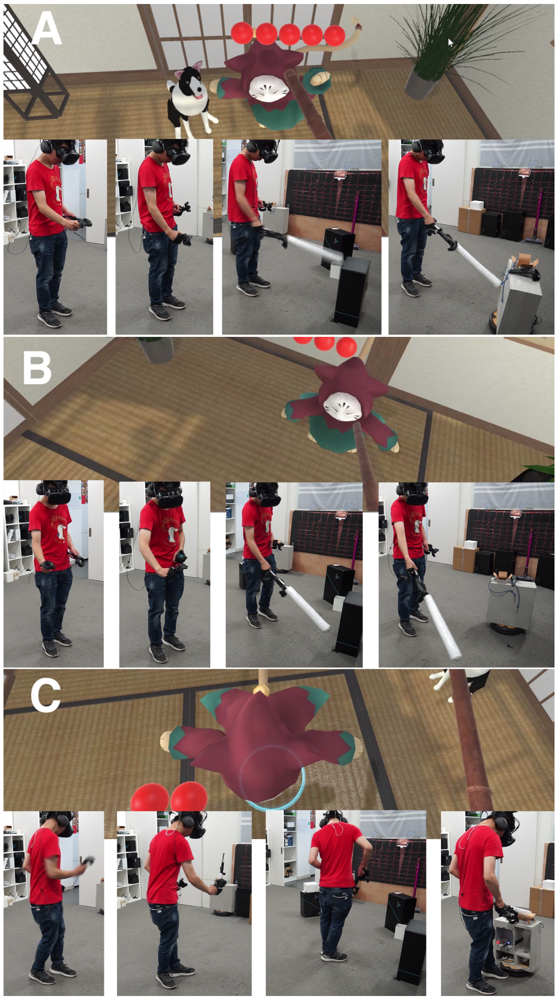

Figure 9. Enemy hitting VR scenario with four haptic conditions. A: The user strikes the enemy successfully. B: The enemy avoids a strike from the user. C: The enemy attacks the user and the user striking back.

Procedure

Users were briefed about the purpose of the study and shown a walk-through demo VR video of the game. The different haptic feedback methods with the elements in the VR demo were explained for each system. We used a within-subject design. Hence each user participates in all four haptic conditions with the order counter-balanced. In each condition, we physically guided the participant into the lab with a completely black screen HMD to avoid users seeing the physical setup. We repeated the above trial twice for each condition. After each condition, participants were asked to fill out a questionnaire that asked them to rate each scenario using a 7 point Likert scale (1: Worst - 4: Neutral - 7: Best). The questionnaire asked users to rate the realism (Q1) and enjoyment (Q2) of the whole VR experience, as well as how easy acceptable of each haptic solution (Q3). When answering the questionnaire, participants were encouraged to think aloud and provide their reasons and comments (Q4). After the overall rating, the user was asked to answer Q1, Q2, Q3 and Q4 for each haptic feedback (tension in dog walking scenario, resistance in box pushing scenario, reaction in enemy hitting scenario and impact in enemy attacking scenario). In total, users finished 16 questions for each haptic condition. Lastly, users reviewed their behavior inside the lab via a video recording. They were allowed to review/modify their scores and provide comments.

Results

We analyze and report the key results and findings in this section. We use within-subject one-way ANOVA with Tukey post-hoc test for significance analysis.

MoveVR can provide more realistic (average score 6.24/7) and enjoyable (average score 6.25/7) VR experiences than commercially available no haptic feedback (***barehand***) and vibration feedback (***vibrotactile haptic***) solutions. There are significant difference in realism rating ($F_{(3,60)} = 5.37, p = 0.002$) and enjoyment rating ($F_{(3,60)} = 10.14, p < 0.001$) among four conditions. Figure 10 shows that participants perceived the virtual world as more realistic and enjoyable in the ***MoveVR*** condition compared to the ***barehand*** ($p = 0.008$ for realism, $p < 0.001$ for enjoyment) and ***vibrotactile haptic*** ($p = 0.03$ for realism, $p = 0.008$ for enjoyment) conditions. However, there is no significant difference between ***MoveVR*** and ***passive haptic*** conditions. Participants did not find *MoveVR* to increase the acceptance burden ($F_{(3,60)} = 0.51, p = 0.68$) compared to other conditions. Here, an increased acceptance burden means that the user will find the method harder to accept.

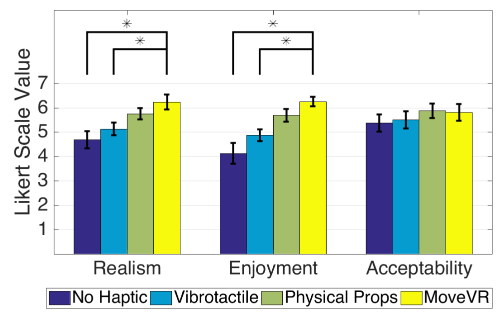

Figure 10. Overall Likert score of four conditions. Error bar indicates the standard error of the mean. * indicates significant difference between two conditions with p <0.05.

MoveVR enables instant force feedback making the interaction smoother by providing users more intuitive feedback clues. In **hit** and **attack** tasks of the enemy hitting scenario, we observed an average of 2.54 times repeated hits in **barehand** condition, 1.87 times repeated hits in **vibrotactile feedback** condition, and 1.13 times hits in ***passive haptic*** condition. In contrast, we found ***MoveVR*** has fewer hits with an average of 1.06 times.

We received some positive comments from the participants in regards to the different VR scenarios using *MoveVR*. 8 participants commented that "It made the VR experience more real and compelling." 7 participants commented that "I really like how the cleaning robot interacted with me. It feels like I was really walking a dog or hitting an enemy." after watching the video recording, P1, P8, P10 and P22 said "I didn't realize that there was only one robot interacting with me. It was amazing." P5, P7 and P15 commented that "It surprises me that the enemy attacked me in both the virtual and the real world. It made the game more real and interesting." P12 and P19 said "I can tell where the attack came from instantly. It is way better than other conditions where I need to look around to identify the enemy." P7 and P13 said "Hitting a physical object provides quicker feedback in knowing whether or not I had hit or missed the enemy." To further explore the user preference on *MoveVR*, we dive into each force feedback expression.

Tension Force Feedback in Dog Walking Scenario

MoveVR significantly outperforms the other three haptic conditions providing more realistic (average score 6.25/7) and enjoyable (average score 6.25/7) VR experiences through active tension force feedback as Figure 11A indicates. There are significant differences in realism rating ($F_{(3,60)} = 8.97, p < 0.001$) and enjoyment rating ($F_{(3,60)} = 9.42, p < 0.001$) among the four haptic conditions. 22 participants rated ***MoveVR*** to be the most realistic and enjoyable among all four conditions.

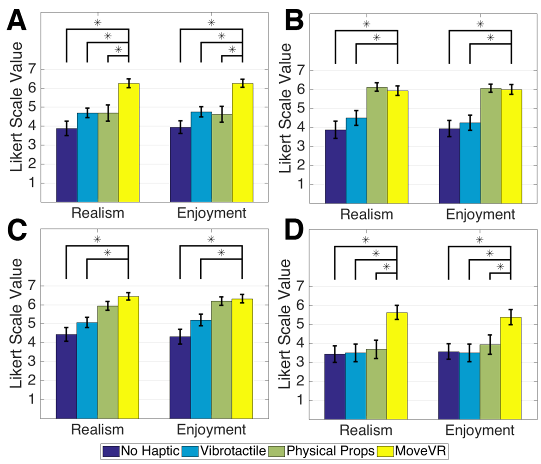

Figure 11. A: Likert scores of continuous pulling force feedback (dog leading scenario). B: Likert scores of resistive force feedback (box pushing scenario). C: Likert scores of reaction force feedback (enemy hitting scenario). D: Likert scores of impact force feedback (enemy attacking scenario). Error bar indicates the standard error of the mean. * indicates significant difference between two conditions with p <0.05.

Resistance Force Feedback in Box Pushing Scenario

Both ***MoveVR*** and ***passive haptic*** significantly outperform ***barehand*** and ***vibrotactile haptic*** conditions. ***MoveVR*** has average scores of 5.94/7 and 6.12/7 respectively for realism and enjoyment rating. There are significant differences for realism ($F_{(3,60)} = 10.47, p < 0.001$) and enjoyment ($F_{(3,60)} = 11.18, p < 0.001$) among four haptic conditions. There is no significant difference between ***MoveVR*** and ***passive haptic*** conditions.

Reaction Force Feedback in Enemy Hitting Scenario

MoveVR significantly outperforms ***barehand*** and ***vibrotactile haptic*** conditions providing more realistic (average score 6.44/7) and enjoyable (average score 6.31/7) user experiences. There are significant differences for realism ($F_{(3,60)} = 10.65, p < 0.001$) and enjoyment ($F_{(3,60)} = 10.09, p < 0.001$) among four haptic conditions. There is no significant difference between ***MoveVR*** and ***passive haptic*** conditions.

Impact Force Feedback in Enemy Attacking Scenario

MoveVR was rated to be significantly higher than all other conditions as Figure 11 indicates. There are significant differences for realism ($F_{(3,60)} = 5.63, p = 0.002$) and enjoyment ($F_{(3,60)} = 9.42, p < 0.001$) among four haptic conditions. *MoveVR* can simulate realistic (average score 5.63/7) and enjoyable (average score 5.38/7) VR experience through impact force feedback.

DISCUSSION AND FUTURE WORK

MoveVR enables realistic multi-level diverse force feedback for virtual reality using a common household cleaning robot. We showed that our technique is capable of simulating multiple levels of tension, reaction, resistance and impact force in VR environment. We proved that users could perceive these expressions accurately by a force perception study. Through a user experience study, we observed that *MoveVR* provides a more realistic and enjoyable VR experience to users compared to commercially available vibrotactile feedback solutions. *MoveVR* has similar evaluation results when compared to passive haptic feedback using a physical props. This means that *MoveVR* can provide realistic and enjoyable force feedback just as good as real-world physical objects, while at the same time has much more scalability, not dependent on human labor for pre-arranging these physical objects in the VR scene. In this section, we discuss in more detail our findings, design guidelines, and future work.

Making Force Feedback More Accessible in VR

Household cleaning robots are becoming commonplace home appliances. We envision a future where the cleaning robots can support interactive VR game play through over the air software updates without any hardware modification. Furthermore, techniques we explored could also be applied to other motorized platforms such as RC cars. Future work can further explore multiple collaborative robot solutions for more expressive force feedback solutions.

MoveVR allows end-users to fabricate and experience a variety of realistic and enjoyable VR applications using everyday materials and objects. However, it requires users to manually assemble the proxy in advance. One possible approach for developers to achieve such goal is to provide assembly guidelines along with the VR application for easy set up of the technology.

Reconfiguration and Collision Avoidance of MoveVR

MoveVR can dynamically repurpose carry-on proxies because of the robot's mobile nature. In our user experience study, *MoveVR* took the role of a dog, a box, and an enemy. We observed that *MoveVR* demonstrated less unnecessary user encounters when compared to solutions using passive physical props. We achieved this by dynamically controlling the robot to avoid collision with the user. We recommend that future developers and content designers create scenarios that allow *MoveVR* enough time to move to the next targeted position, while keeping enough distances from users (around 1 meter according to our experience) to avoid collision. We would like to explore leveraging built-in SLAM algorithms with an existing environment map to avoid unnecessary collision in our future work. In our current setup, users may accidentally hit the robot before the enemy was rendered in the VR scene. We could further reduce unnecessary force feedback in our future work by taking the user's posture into considering in our path-finding algorithm.

Fabricating and Assembling MoveVR

We proposed simple fabrication and assembly methods using common household tools, objects and materials. We would like to further evaluate and improve the fabrication process to help lower the bar for users to replicate *MoveVR* proxies with pre-designed instructions. As far as materials are concerned, we highly recommend soft package foams since they can be easily customized into different shapes to fit various scenarios. We selected touch fasteners and tapes due to their cheap and lightweight features. Touch fasteners can deliver strong horizontal shear strength ($20-30N/cm^2$) while tape can deliver strong vertical peel strength. We would like explore other assembly methods such as magnets based attachment methods which can automatically attach without requiring precise visual alignment.

Force Expression Capability Using MoveVR

We showed that *MoveVR* could deliver multi-level multiform force feedback. However, we have not yet explored the resolution limit of each expression or measure the maximum reaction and impact force intensity. Furthermore, exploring dynamic coordination between the robot's and the user's orientation [27] could help to enable finer granular force feedback.

Structural Constrains of the Cleaning Robot

Although cleaning robots are becoming more accessible to end-users, there are some structural constraints in using them for VR force feedback. The first limitation is their physical speed (measured maximum speed of 435mm/s). The slow movement creates lag when moving the robot to a targeted position, which affects the overall responsiveness of the system. One possible solution is to alternate between force feedback and other tasks that solely rely on visual feedback to give the robot more time to reach its destination. Furthermore, better proportional integral derivative (PID) algorithm would also allow the robot to get to its targeted position using less time.

Another limitation of *MoveVR* is the Roomba's wheel system. Its physical shape creates unrealistic sensations, which is most evident in the box pushing scenario. 2 users mentioned that they were able to feel the irregularities in the force feedback coming from wheels when pushing the box. In addition, the cleaning robot usually has two driving wheels at the back and one universal wheel in the front, which causes the roomba to tilt when pushed sideways. The roomba's facing should be adjusted according to the user's location to avoid tilting.

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CONCLUSION

With the increasing popularity of household cleaning robots in recent years, we envision these robot enabling easy-to-access haptic feedback applications in virtual reality. In this paper, we present *MoveVR*, a new technique that leverages household cleaning robots to provide multiform force feedback for immersive VR experiences. *MoveVR* can generate tension, resistance, reaction and impact sensations with multiple levels of intensity by changing the robot's moving speed, position as well as the carried proxies. In our evaluation study, we demonstrated that *MoveVR* can deliver distinguishable multilevel force feedback including force intensity, force direction and material rigidity with high user perception accuracy. We further showed that *MoveVR* can render more realistic and enjoyable VR experiences with similar user acceptance when compared to commercially available vibrotactile solutions, while having the advantage of scalability and versatility in applications when compared to passive physical proxy alternatives.

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