Demonstrating HapticBots

Distributed Encountered-type Haptics for VR with Multiple Shape-changing Mobile Robots

Ryo Suzuki, Eyal Ofek, Mike Sinclair, Daniel Leithinger, Mar Gonzalez Franco
[1]University of Calgary, [2]Microsoft Research, [3]University of Colorado Boulder
ryo.suzuki@ucalgary.ca,{eyalofek,sinclair,margon}@microsoft.com,daniel.leithinger@colorado.edu

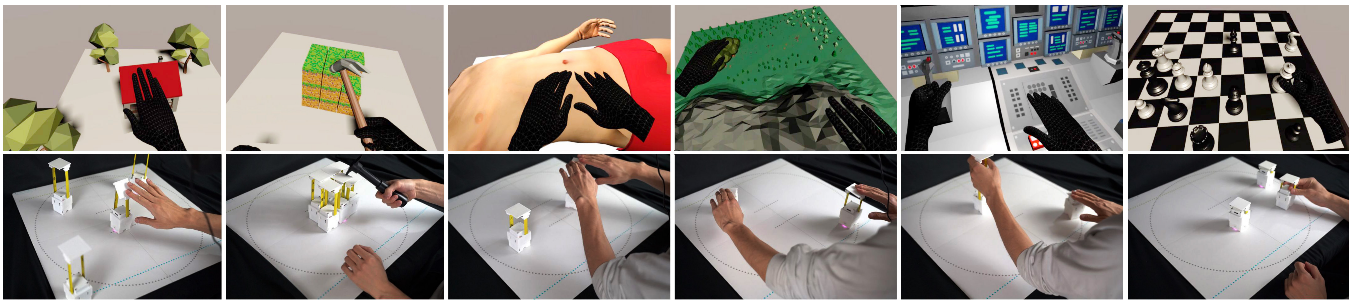

Figure 1: HapticBots render encountered-type haptics for a range of VR applications.

ABSTRACT

HapticBots introduces a novel encountered-type haptic approach for Virtual Reality (VR) based on multiple tabletop-size shape-changing robots. These robots move on a tabletop and change their height and orientation to haptically render various surfaces and objects on-demand. Compared to previous encountered-type haptic approaches like shape displays or robotic arms, our proposed approach has an advantage in deployability, scalability, and generalizability—these robots can be easily deployed due to their compact form factor. They can support multiple concurrent touch points in a large area thanks to the distributed nature of the robots. We propose and evaluate a novel set of interactions enabled by these robots which include: 1) rendering haptics for VR objects by providing just-in-time touch-points on the user's hand, 2) simulating continuous surfaces with the concurrent height and position change, and 3) enabling the user to pick up and move VR objects through graspable proxy objects. Finally, we demonstrate HapticBots with various applications, including remote collaboration, education and training, design and 3D modeling, and gaming and entertainment.

CCS CONCEPTS

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

KEYWORDS

virtual reality; encountered-type haptics; tabletop mobile robots; swarm user interfaces

ACM Reference Format:
Ryo Suzuki, Eyal Ofek, Mike Sinclair, Daniel Leithinger, Mar Gonzalez Franco. 2021. Demonstrating HapticBots: Distributed Encountered-type Haptics for VR with Multiple Shape-changing Mobile Robots. In *UIST '21: ACM Symposium on User Interface Software and Technology, October 10–13, 2021, Virtual.* ACM, New York, NY, USA, 3 pages. https://doi.org/10.1145/1122445.1122456

1 INTRODUCTION

Encountered-type haptics [4, 15] have been introduced to provide haptic sensations through *actuated physical environments* by dynamically moving physical objects [1, 2, 9] or transforming the physical shape [5, 7, 10, 13] when the user encounters the virtual object. Different approaches have been developed for encountered-type haptics: from grounded robotic arms (e.g., Snake Charmer [1], VRRobot [14]) to shape displays (e.g., shapeShift [7], Feelex [3], inForce [5], Auxetic Shape Display [8]).

However, the current approaches still face a number of challenges and limitations. For example, shape displays often require large, heavy, and mechanically complex devices, reducing reliability and deployability of the system for use outside research labs. Also, the resolution fidelity and the display's size are still limited, making it difficult to render smooth and continuous surfaces across a large interaction area. Alternately, robotic arms can bring a small piece of a surface to meet the user hand on demand, but the speed at which humans move challenges the ability to cover just in time large interaction spaces with a single device. Scaling the number of robotic arms is also a challenge as complex 3D path planning is required to avoid unnecessary collision with both the user and the other arms.

The goal of this paper is to address these challenges by introducing a novel encountered-type haptics approach, which we call

UIST '21, October 10–13, 2021, Virtual

ACM ISBN 978-1-4503-XXXX-X/18/06...$15.00
https://doi.org/10.1145/1122445.1122456

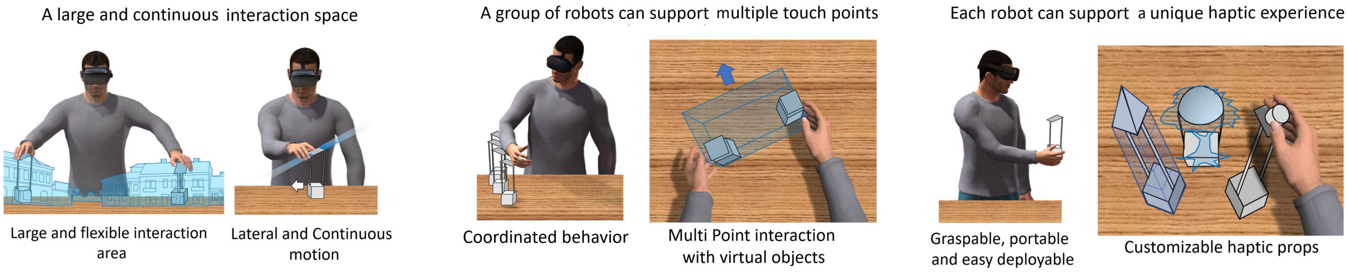

Figure 2: Unique features of distributed encountered-type haptics. First, our freely moving robots can reach and render touch points in a large interaction space. Accurate rendering of 3D locations and orientations of surfaces (left). The use of multiple robots can generate multiple touch events concurrently (middle). Finally, each robot can be regarded as a separate object that may be picked up, moved around, and the payload that it carries can be uniquely fitted to the application

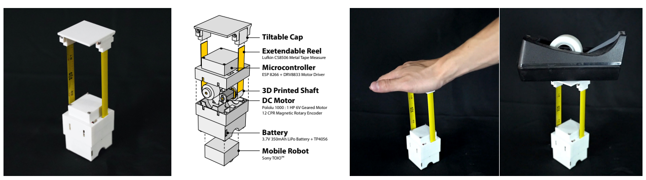

Figure 3: Left: Mechanical design of the reel actuator. Right: The actuator maximum holding load is 1379 g at the extended state (25 cm height)

distributed encountered-type haptics. Distributed encountered-type haptics employ multiple shape-changing mobile robots to simulate a consistent physical object that the user can encounter through hands or fingers. By synchronously controlling multiple robots, these robots can approximate different objects and surfaces distributed in a large interaction area. Our proposed approach enables *deployable*, *scalable*, and *general-purpose* encountered-type haptics for VR, providing a number of advantages compared to the existing approaches.

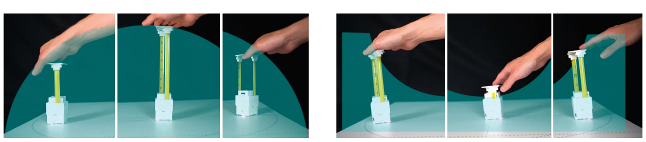

Figure 4: A single robot simulates a virtual surface.

The main contribution of this paper is a concept of this novel encountered haptic approach and a set of distributed interaction techniques. To demonstrate this idea, we built *HapticBots* [11], a tabletop shape-changing mobile robots that are specifically designed for distributed encountered-type haptics. HapticBots consists of off-the-shelf mobile robots (Sony TOIO), and custom height-changing mechanisms to haptically render general large surfaces with varying normal directions (-60 to 60 degrees). It can cover a large space (55 cm × 55 cm) above the table (a dynamic range of 24 cm elevation) at high speed (24 cm/sec and 2.8 cm/sec for horizontal and vertical speed, respectively). Each robot is compact (4.7 × 4.7 × 8 cm, 135 g) and its tracking system consists of an expandable, pattern-printed paper mat; thus, it is portable and deployable.

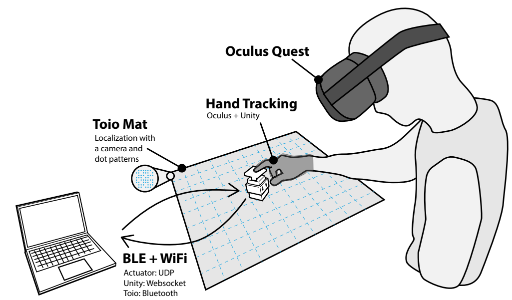

Figure 5: System Setup: The Oculus Quest VR Headset is calibrated to work in the same coordinate space as the tracked robots (right).

Our HapticBots' hardware design is inspired by the existing shape-changing swarm robots like ShapeBots [12] or HERMITS [6], but as far as we know, our system is the first exploration of using multiple tabletop shape-changing robots for VR haptics. Applying to VR haptics introduces a set of challenging requirements, which led to a new distributed haptics system design as well as to new hardware for each of the robots: *1) Efficient path planning integrated with real-time hand tracking:* The system coordinates the movements of all robots with the user's hand. We track and anticipate potential touch points at a high frame rate (60 FPS) and guide the robots to encounter the user's hands in a just in time fashion. *2) Precise height and tilt control:* In contrast to ShapeBots' open-loop system, HapticBots enables more precise height and tilt control with embedded encoders and closed-loop control system to render surfaces with varying normal angles. *3) Actuator robustness:* We vastly improved actuator force by around 70x (21.8N vs. 0.3N holding force of [12]) to provide meaningful force feedback.

This paper contributes to the new concept, a set of haptic interaction techniques, and its demonstration with HapticBots system. We also demonstrate various haptic applications for different VR scenarios, including training, gaming and entertainment, design, and remote collaboration.

REFERENCES

[1] Bruno Araujo, Ricardo Jota, Varun Perumal, Jia Xian Yao, Karan Singh, and Daniel Wigdor. 2016. Snake charmer: Physically enabling virtual objects. In *Proceedings of the TEI'16: Tenth International Conference on Tangible, Embedded, and Embodied Interaction*. 218–226.

[2] Zhenyi He, Fengyuan Zhu, and Ken Perlin. 2017. Physhare: Sharing physical interaction in virtual reality. In *Adjunct Publication of the 30th Annual ACM Symposium on User Interface Software and Technology*. 17–19.

[3] Hiroo Iwata, Hiroaki Yano, Fumitaka Nakaizumi, and Ryo Kawamura. 2001. Project FEELEX: adding haptic surface to graphics. In *Proceedings of the 28th annual conference on Computer graphics and interactive techniques*. 469–476.

[4] William A McNeely. 1993. Robotic graphics: a new approach to force feedback for virtual reality. In *Proceedings of IEEE Virtual Reality Annual International Symposium*. IEEE, 336–341.

[5] Ken Nakagaki, Daniel Fitzgerald, Zhiyao Ma, Luke Vink, Daniel Levine, and Hiroshi Ishii. 2019. inFORCE: Bi-directionalForce'Shape Display for Haptic Interaction. In *Proceedings of the thirteenth international conference on tangible, embedded, and embodied interaction*. 615–623.

[6] Ken Nakagaki, Joanne Leong, Jordan L Tappa, João Wilbert, and Hiroshi Ishii. 2020. HERMITS: Dynamically Reconfiguring the Interactivity of Self-Propelled TUIs with Mechanical Shell Add-ons. In *Proceedings of the 33rd Annual ACM Symposium on User Interface Software and Technology*. 882–896.

[7] Alexa F Siu, Eric J Gonzalez, Shenli Yuan, Jason B Ginsberg, and Sean Follmer. 2018. Shapeshift: 2D spatial manipulation and self-actuation of tabletop shape displays for tangible and haptic interaction. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems*. 1–13.

[8] Anthony Steed, Eyal Ofek, Mike Sinclair, and Mar Gonzalez Franco. 2021. A Mechatronic Shape Display based on Auxetic Materials. In *Nature Communications*.

[9] Ryo Suzuki, Hooman Hedayati, Clement Zheng, James L Bohn, Daniel Szafir, Ellen Yi-Luen Do, Mark D Gross, and Daniel Leithinger. 2020. Roomshift: Room-scale dynamic haptics for vr with furniture-moving swarm robots. In *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems*. 1–11.

[10] Ryo Suzuki, Ryosuke Nakayama, Dan Liu, Yasuaki Kakehi, Mark D Gross, and Daniel Leithinger. 2020. LiftTiles: constructive building blocks for prototyping room-scale shape-changing interfaces. In *Proceedings of the Fourteenth International Conference on Tangible, Embedded, and Embodied Interaction*. 143–151.

[11] Ryo Suzuki, Eyal Ofek, Mike Sinclair, Daniel Leithinger, and Mar Gonzalez Franco. 2021. HapticBots: Distributed Encountered-type Haptics for VR with Multiple Shape-changing Mobile Robots. In *Proceedings of the 34th Annual ACM Symposium on User Interface Software and Technology*.

[12] Ryo Suzuki, Clement Zheng, Yasuaki Kakehi, Tom Yeh, Ellen Yi-Luen Do, Mark D Gross, and Daniel Leithinger. 2019. Shapebots: Shape-changing swarm robots. In *Proceedings of the 32nd Annual ACM Symposium on User Interface Software and Technology*. 493–505.

[13] Shan-Yuan Teng, Cheng-Lung Lin, Chi-huan Chiang, Tzu-Sheng Kuo, Liwei Chan, Da-Yuan Huang, and Bing-Yu Chen. 2019. Tilepop: Tile-type pop-up prop for virtual reality. In *Proceedings of the 32nd Annual ACM Symposium on User Interface Software and Technology*. 639–649.

[14] Emanuel Vonach, Clemens Gatterer, and Hannes Kaufmann. 2017. VRRobot: Robot actuated props in an infinite virtual environment. In *2017 IEEE Virtual Reality (VR)*. IEEE, 74–83.

[15] Yasuyoshi Yokokohji, Nobuhiko Muramori, Yuji Sato, and Tsuneo Yoshikawa. 2005. Designing an encountered-type haptic display for multiple fingertip contacts based on the observation of human grasping behaviors. *The International Journal of Robotics Research* 24, 9 (2005), 717–729.