Mediate: A Spatial Tangible Interface for Mixed Reality

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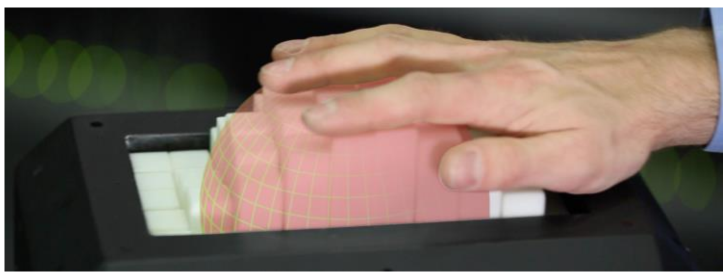

Figure 1: Mediate provides a mobile hand-sized shape-changing surface that renders coincident geometry of the virtual environment.

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Abstract
Recent Virtual Reality (VR) systems render highly immersive visual experiences, yet currently lack tactile feedback for feeling virtual objects with our hands and bodies. Shape Displays offer solid tangible interaction but have not been integrated with VR or have been restricted to desktop-scale workspaces. This work represents a fusion of mobile robotics, haptic props, and shape-display technology and commercial Virtual Reality to overcome these limitations. We present *Mediate*, a semi-autonomous mobile shape-display that locally renders 3D physical geometry co-located with room-sized virtual environments as a conceptual step towards large-scale tangible interaction in Virtual Reality. We compare this “dynamic just-in-time mockup” concept to other haptic paradigms and discuss future applications and interaction scenarios.

Author Keywords
Tangible Interface; Virtual Reality; Robot; Haptic; Hand; Shape Display; Pin Display; Robotic Graphics

ACM Classification Keywords
H.5.2. Information Interfaces and Presentation: Haptic I/O.

Figure 2: A user touches a virtual object on the pedestal-size mobile shape display.

Introduction

The advent of commercial VR platforms - such as the HTC Vive and Oculus Rift - has recently allowed for practical rendering of highly immersive visual experiences. However, corresponding haptic technology has struggled to provide meaningful tactile sensations that are similarly rich, dynamic, and spatially informative. Current solutions are limited in either fidelity, working area, or practicality and convenience. In VR, we can see far more than we can feel.

Large actuated pin arrays, or "Shape Displays" [11] represent a powerful paradigm for general-purpose tangible interfaces that render real physical shapes with no additional wearable gear, allowing full-body interaction. However, traditional Shape Displays have been limited to tabletop working areas because adding mechanically actuated pins to create a larger array is not practically scalable to room-sized experiences (and enlarging the pins reduces tactile fidelity).

Mediate functions similarly to previous Shape Displays. With only 50 pins, it has a relatively small work volume. [Figure 1]. However, during interaction, it achieves a large *effective* workspace by moving itself around the room while tracking the user's hands. The shape rendered is only a hand-sized portion the larger virtual environment. The pins conform to virtual surfaces as the device moves around coincident physical and virtual worlds. The independent mobility of this "on-demand prop" allows users to explore large virtual environments, especially when used in conjunction with visuals from Head-Mounted Displays (HMD).

Figure 3: A user wearing an HMD interacting with a virtual object simultaneously rendered physically on *Mediate*

While Shape Displays, Robotic Interfaces, Virtual Reality, Hand-Tracking, and their integration in various combinations [1, 6, 7, 9, 12, 15, 18, 19, 20] are not novel, we believe the design paradigm demonstrated by this system, focusing on mobility, represents a significant conceptual step towards the goal of tangible interaction in room-scale Virtual Reality. With that goal, this contribution should be considered first as a spatial haptic interface for Virtual Reality that utilizes the unique capabilities of robotics and Shape Displays, and second as an extension of Shape Display technology into large-scale immersive Virtual Reality interactions.

In the following sections, we describe the technical design of Mediate, compare the system to previous work, and discuss future applications and interaction scenarios.

Technical Specifications

Pins
$20mm \times 20mm \times 100mm$ white ABS plastic, arranged in 5×10 array on $1.5m$ height pedestal

Pin Movement
$100mm$ range with $18\mu m$ resolution at $1\frac{m}{s}$ @ $20\frac{m}{s^2}$

Pin Actuator
Faulhaber "Quickshaft" LM1247-120-11 linear DC motors with *MCLM-3002-P-CO* motion controllers

Communication
$200Hz$ motor controller global refresh over $10 \times$ Controller Area Networks (CAN), 1MBaud Serial *USB3.0* with host computer

Microcontrollers
$10 \times$ Arduino Teensy Microcontrollers (72MHz ARM Cortex-M4)

Robot Movement
$1\frac{m}{s}$ max software limit, omnidirectional motion

3D Tracking
6-DOF sub-mm @ $60Hz$ within $3.5m^2$ (SteamVR)

Power
5 $\times$ XP Power SHP65PS28, each 23A @ 28V

System Design and Overview

The Mediate interface consists of an array of 50 actuated square pins mounted on top of a mobile robotic “pedestal” (Figure 4.) An omnidirectional motorized wheelbase allows the entire device to drive in any horizontal direction while rotating about its vertical axis. The 6-Degrees-of-Freedom (DOF) pose of the display is tracked by the SteamVR indoor tracking system [17] (used by the HTC Vive Virtual Reality system). This real-time sub-mm accuracy tracking allows the display to be co-located with a virtual geometry situated in the real space.

A hand-tracking sensor (Leap Motion Controller) is mounted above the pin array to track a user's hand as they explore the environment while the mobile base autonomously follows and aligns to the user's hand. (Software limits on velocity and acceleration, appropriate for walking-speed movement, are imposed for safety.)

At any given time, the height of each pin is determined by casting a ray from the pin’s maximum position to its default height, colliding with the “highest” virtual geometry in-between. The pins thus conform to geometric surfaces as the display translates and rotates “underneath”. (The algorithm applies to arbitrary 3D positions and orientations, but the device is physically designed for operation near vertical.)

The interaction scenarios and software are implemented in the Unity3D game engine running on a host computer, which also drives the HMD visuals. A semi-transparent model of the device is always overlaid in VR for situational awareness and safety.

Related Work

Haptic Interfaces

Haptic interfaces may be grouped into two categories. On-body devices include haptic gloves, vibrotactile suits, and hand-held controllers [2]. Because they are attached to a user’s body, these devices have the advantage of being intrinsically mobile (unlimited usable work area), but also the inherent disadvantages of being unable to apply external forces and encumbering the user. External haptic devices include 3D Styluses [13], in-air haptic displays [3], and Shape Displays [4]. By contrast, these systems can provide external forces and often feature superior tactile fidelity but are usually immobile and have generally proved difficult to build with large usable interaction volumes.

Robotic Graphics

A compromise between the free movement of on-body devices and the capabilities of independent systems was proposed by McNeely [14] as Robotic Graphics and Robotic Shape Displays (RSDs). These systems are not worn by the user, but can track and react to their movement to render tactile feedback according to virtual or physical models [1,6].

The "virtual mockup" interaction of Mediate conceptually resembles RSDs with two key improvements: 1) An independent mobile platform enables large-scale work volumes 2) A dynamically-changing interaction surface overcomes the primary limitation of RSDs in supporting only "very simple […] shapes". Recently, Siu et al. presented a similar system [16] that also enables Robotic Graphics using a mobile actuated pin array specifically for tabletop interaction. In contrast, Mediate is designed to move with a user as they walk through room-scale virtual environments.

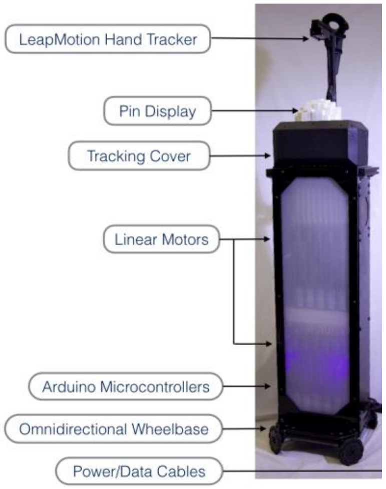

Figure 4: Mediate System Components

Potential Applications

Tangible Interaction with Large Virtual Geometry

The primary goal of Mediate is to demonstrate, in a 3D-tracked portable hand-sized shape display, a spatially scalable solution to hi-fidelity tactile feedback for virtual and augmented reality. Where previous shape displays only allowed interaction with objects smaller than their work area, Mediate allows interaction with geometry larger than its pin array by moving itself across the virtual environment in anticipation of users' touch. From the user's perspective, as long as the device keeps up with their hands and positions itself wherever they are about to reach, the display is effectively "infinite." This opens opportunities for high-fidelity (µm scale) haptic interaction even with large (meter scale) virtual objects. To demonstrate the capability and practicality of Mediate for room scale interaction, here we discuss a range of potential applications.

Telepresence and Remote Collaboration

Multiple Mediate displays would allow several users to interact with the same synchronized virtual environment, either in the same room or across the planet, with physical changes in one display reflected in real time by another. Although this has been previously demonstrated with either tangible displays or VR systems, Mediate combines both interface types to allow "heterogeneous" users - some users can perceive the virtual world through vision alone using HMDs, while others can use Mediate displays to both see and touch. Multiple users may also share the same Mediate display by taking turns or touching simultaneously. More importantly, the large size of the common environment allows users to perceive both spatial presence of and tangible connection with each other.

Games and Entertainment

The ability of Mediate to locally bridge physical and virtual environments offers new interaction modes for mixed-reality games and storytelling. For example, "hide-and-seek" or "treasure-hunt" - style games would be easily implemented with virtual objects hidden in the real room, waiting to be "revealed" by the display.

Physical Animation

Mediate can be programmed to navigate autonomously, following pre-programmed paths or patterns, in addition to animating its pins. This allows the display to show dynamic physical motions on previously impossible scales. For example, Mediate could be used to show the orbit of a planet wherein the pins create a sphere shape while the mobile base drives in an "orbit" around the entire room. Users could also "teach" a trajectory to the system by guiding it with their hand.

Demonstration and Discussion

Interaction and Gestures

The prototype was demonstrated in an "open lab event" where approximately 100 people interacted with a virtual sphere. During this initial testing, most users found it easier to alternately move their guiding hand in front of the robot and then feel shapes, rather than continuously touching the pins while guiding. Some preferred an alternative guiding method of tilting their hand in the desired travel direction while keeping it near the center of the array, rather than leading ahead. Both of these techniques are promising methods of utilizing hand gestures for guiding mobile robots. Future in-air hand gestures could be incorporated, allowing the user to "push" and "pull" on the pins as with previous shape displays.

Physical Proximity
Users tend to interact with the device at arm's length, and therefore rarely contact other parts of the machine than the pins. We suspect this inclination is to prevent collision with the base. Users consistently maintain this behavior even while wearing an HMD (they can still see the translucent model of the device overlaid on its actual position). Sharp pin edges and occasional jerky motions remain problematic for user comfort.

Limitations and Future Work

Temporal and horizontal spatial resolution are adequate for the interactions described above. Vertical resolution, however, remains a priority for future improvement. The display is limited to rendering a single geometric surface between 1.5m - 1.6m high. All other geometry is occluded, as are shapes with steep angles or overhangs. In principle, the entire display can be tilted or elevated to render slanted geometry or higher/lower objects respectively. This functionality was possible in testing but it proved physically arduous for most users due to the size and weight of the device. Therefore, mechanizing these DOFs would be another next step in advancing the current system. Namely, the entire display could be mounted on a custom gimbaling elevator as in Figure 5, or on an industrial robot arm. These mechanizations were considered, but not pursued in this work due to resource constraints as well as favor for an aesthetic design and pedestal form-factor evocative of previous shape displays [6].

Conclusion

Motivated by a desire to combine the advantages of standalone tactile interfaces with portable haptic devices, we developed *Mediate*, a mobile shape display for room-scale tactile interaction with virtual environments. Mediate utilizes a relatively small shape display while achieving room-scale usable volumes through autonomous mobility. As a hybrid between pin-based Shape Displays, McNeely's Robotic Graphics, and commercial VR technology, this work represents a powerful conceptual step towards scalable dynamic tangible rendering of large virtual geometry in room-scale environments.

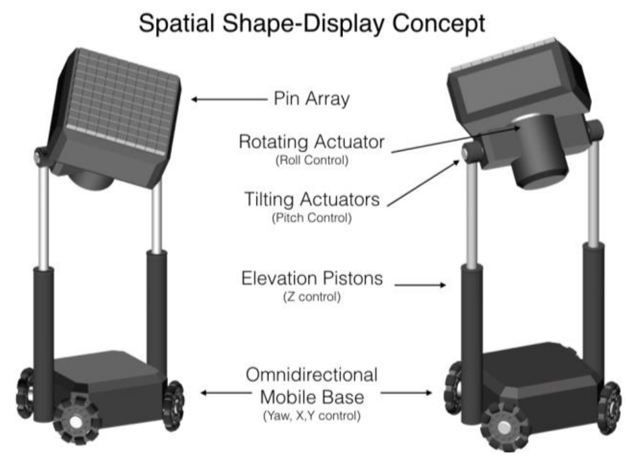

Figure 5: A future version of Mediate would conform to a range of geometry heights and angles.

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