

CARNEGIE MELLON UNIVERSITY

School of Architecture
College of Fine Arts

Thesis

Submitted in Partial Fulfillment of the requirements for the degree of

Master of Science in Computational Design

TITLE:

***HADEN – Using Virtual Reality as an Expressive Medium
for Spatial Design***

AUTHOR:

Qiaozhi Wang

ACCEPTED BY ADVISORY COMMITTEE:

Principal Advisor

Assistant Prof. Daniel Cardoso Llach, Ph.D.

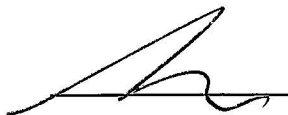


Date

MAY 18 / 17

Advisor

Assistant Teaching Prof. Eddy Man Kim



Date

5/18/2017

***HADEN – Using Virtual Reality as an Expressive Medium for
Spatial Design***

By

Qiaozhi Wang

Thesis Advisors:

Daniel Cardoso Llach

and

Eddy Man Kim

*A Master's Thesis submitted in partial fulfillment
of the requirements for the degree of
Master of Science in Computational Design
Carnegie Mellon University - School of Architecture*

2017

Acknowledgements

First, I would like to sincerely thank my academic advisor, Daniel Cardoso Llach, for his expert guidance and full support on my thesis. His advice always points me in the right direction and keeps motivating me to push further.

Second, I would like to thank my committee advisor, Eddy Man Kim, for his insightful advice and feedback. Also, I'm deeply grateful for his efforts in making CodeLab a perfect place for VR research.

Thanks to all my friends at MSCD: Amit Nambiar, Ardavan Bidgoli, Darcy (Hetian) Cao and Lu Han, for their supports and encouragements. Their passion and friendship always put a smile on my face and inspire me to continue my work.

Thanks to Ben Scott and Kaleb Crawford for their brilliant work on VRUX, which serves as the foundation as well as a source of inspiration for my project.

I'm very grateful to Robert Zacharias for his generous help on my thesis and his efforts in making CodeLab a friendly and supporting environment.

Thanks to Chaoya Li, Dan Moore, Jen Liu, Hexing Ren, Hugh Dyar, Irene Alvarado, Rehan Butt and all the friends at CodeLab and School of Architecture, for making these past two years at Carnegie Mellon University a great experience and meaningful journey of my life.

Last but not least, I'm deeply indebted to my parents and grandparents for their years of support in my education and placing their complete confidence in me. I couldn't be grateful enough for their sacrifice and understanding.

Again, thank you all.

Abstract

Recent developments in Virtual Reality have brought a resurgence of interest in incorporating Virtual Reality with computer-aided design to help designers better express their ideas and thinking. Current computer-aided design interfaces are not intuitive enough for designers to be creative in the conceptual stage of spatial design. This thesis explores the use of Virtual Reality as an intuitive and expressive spatial design medium through the physical embodiment of design interfaces. It proposes a design system, HADEN (HAptic DEsign iNterface) which provides passive haptic feedback by overlapping real and virtual objects using a motion tracking system. This novel tangible user interface not only improves one's sense of presence in VR but also increases the affordances of the virtual interface. Designers can freely generate spatial designs and explore new design alternatives and ideas at the same time.

Keywords: Virtual Reality; Tangible User Interface; Passive Haptics; Computer-Aided Design;

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1 Introduction

1.1 The Evolution of Design Media

“Medium is the message. This is merely to say that the personal and social consequences of any medium-- that is, of any extension of ourselves -- result from the new scale that is introduced into our affairs by each extension of ourselves, or by any new technology.”

Understanding Media The extensions of man (McLuhan, 1964)

The history of design is also a history of evolving design tools and media. Notably, drawing is one of the most essential media for us to express our thoughts and creativities. We have been using drawings to extend ourselves and preserve our mind through thousands of years of history. The earliest cave painting can be dated back to at least 40,000 years ago (Aubert et al., 2014).

In early 15th century, Italian architect Filippo Brunelleschi re-discovered the linear perspective technique through experiments of drawing perspective pictures of the Baptistery of Florence and the Palazzo Vecchio. These pictures were produced by drawing on top of the reflection of a mirror such that its perspective is perfectly aligned with the real scene (Edgerton, 1975).

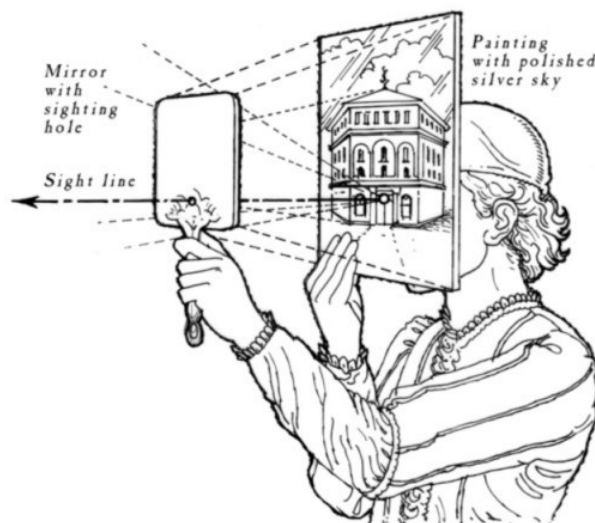


Figure 1 Brunelleschi's mirror experiment (*maItaly, 2011*)

The discovery of this systematic approach to perspective drawing empowers designers to not only produce artifacts that faithfully reflect the reality we see but also construct fantasies that do not exist but appears believable to our eyes (Latour, 1986). Linear perspective paves the way for future technologies such as computer graphic and computer-aided design.

The earliest discussion of integrating computer into design process dates back to the CAD project at MIT led by Steve A. Coons. Coons's idea of human and machine relationship is by treating computer as a "perfect slave" or "silent partner" so that designers can be emancipated from the tedious jobs and focus on the creative thinking (Cardoso Llach, 2015).

In 1964, one of Coons's students, Ivan Sutherland introduced an interactive drawing system called Sketchpad as part of his Ph.D. thesis at MIT. It runs on the Lincoln TX-2 computer and uses CRT (Cathode Ray Tube) monitor with light pen to achieve interactivity (Sutherland, 1963). This system is considered to be the origin of modern computer-aided design programs because it already incorporated many of the design features still being used today (Cardoso Llach, 2015).

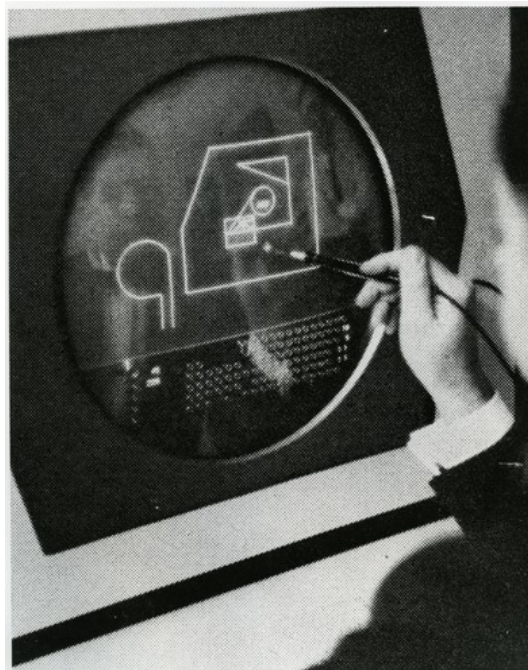


Figure 2 Sketchpad (Sutherland, 1963)

In spite of the technology optimism of the early pioneers, looking back at the history of computer-aided design, today's landscape of CAD software and systems has somewhat deviated from what they had originally envisioned. CAD Software today address more on drafting rather than sketching and drawing; More on efficiency and management rather than creativity and imagination. Coupled with undesirable user interface designs, designers are required to remember large amount of commands and operations and practice for many hours to achieve a high level of proficiency in such software.

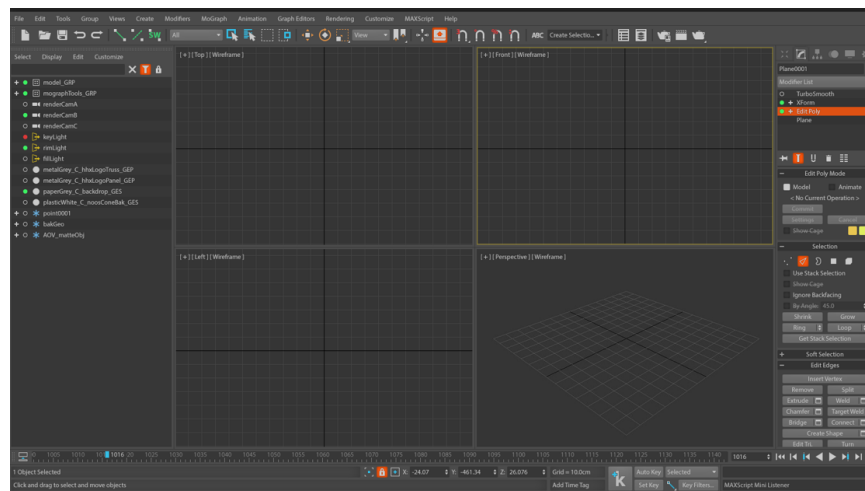


Figure 3 Interface design of modern CAD software (Han Han Xue, 2015)

As a result, designers adopted a more flexible strategy in practice: combining these methods to maximize their advantages. In the early stage, designers tend to use pen and paper to capture their creative whims and conceptual ideas. Then using modelling software to further develop the details. Finally using CAD system and rendering tool to produce precise drafts and photorealistic renderings. This strategy inevitably costs designers a lot of time translating the designs between different tools. Although more recent attempts with BIM software promise to streamline this process, designers still have to deal with the extra learning curve of the software itself and being limited by the ever more complicated interfaces.

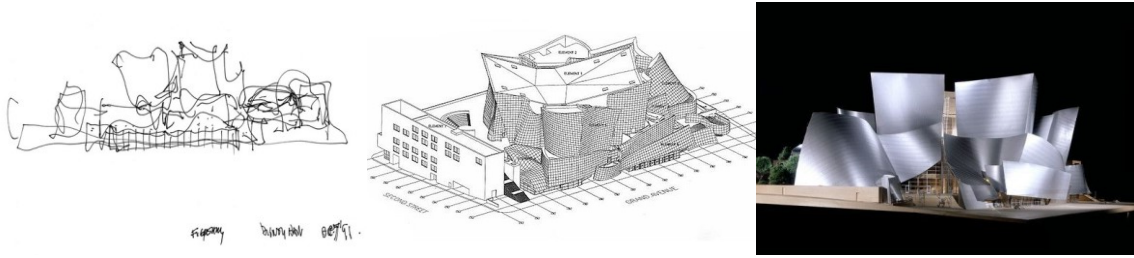


Figure 4 Design workflow of Frank Gehry's Walt Disney Concert Hall
 ("Process | Walt Disney Concert Hall 10th Anniversary," 2014)

1.2 Tools and the Mind

Study has shown that people's mathematical skills may be totally different depending on whether they use paper and pencil or not (Latour, 1986). This indicates that the tools people use may have an impact on their higher cognitive functions. So rather than seeing design tools as neutral media, it would be interesting to ask the following question: How does design tool shape our design thinking? The tools that we take for granted everyday may have been constraining our design capabilities without us even noticing it.

The prevailing paradigm of linear CAD workflow forces designers to plan everything ahead to avoid the back and forth between different tools. However, designers' mind is not linear. In fact, they are constantly exploring, tinkering and having a conversation with the materials, relying on the feedback loop of trial and error to iterate toward a better design (Schön, 1983).

We need a design medium that is expressive enough to be creative, immediate enough to be iterative and responsive enough to be perceptive. Such medium will not only liberate designers' creativity but also introduce new possibilities of design paradigms.

1.3 A History of Virtual Reality

“A display connected to a digital computer gives us a chance to gain familiarity with concepts not realizable in the physical world. It is a looking glass into a mathematical wonderland.”

The Ultimate Display (Sutherland, 1965)

The advent of Virtual Reality is closely connected to the architectural design and computer-aided design field. In 1968, Ivan Sutherland demonstrated the first head-mounted display that used head tracking and real-time computer graphics, known as the Sword of Damocles (Sutherland, 1968).

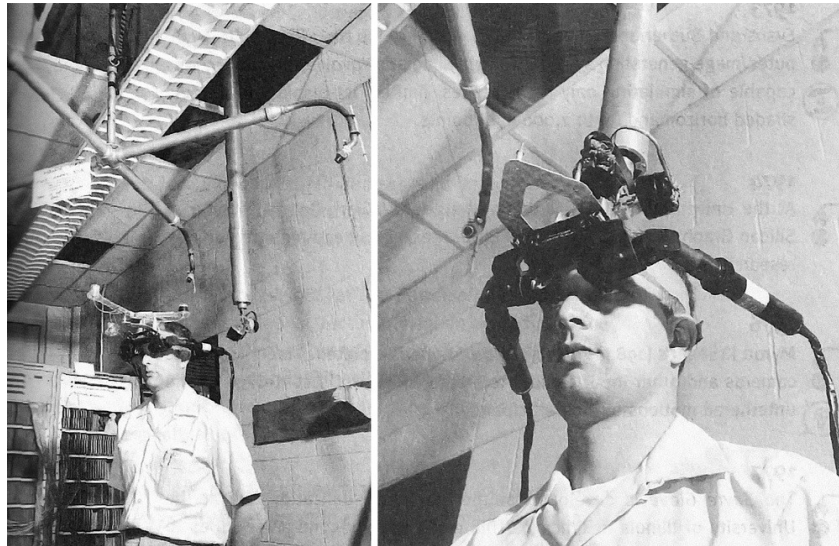


Figure 5 Sword of Damocles
 (“Accessibility of VR: The Future of Virtual Reality,” 2016)

The Hype and the Burst

In the 1990s, people had high expectations about the future of VR. Companies such as Virtuality and Nintendo went into the market to produce VR headsets and interactive peripherals (Jerald, 2015). In mainstream media, Virtual Reality was depicted as the imminent future of telepresence and virtual utopia (Robertson & Zelenko, 2014). However, these grand promises were beyond the technological capabilities of that time. As people realized the costly prices yet low performance of VR products, the VR bubble burst.

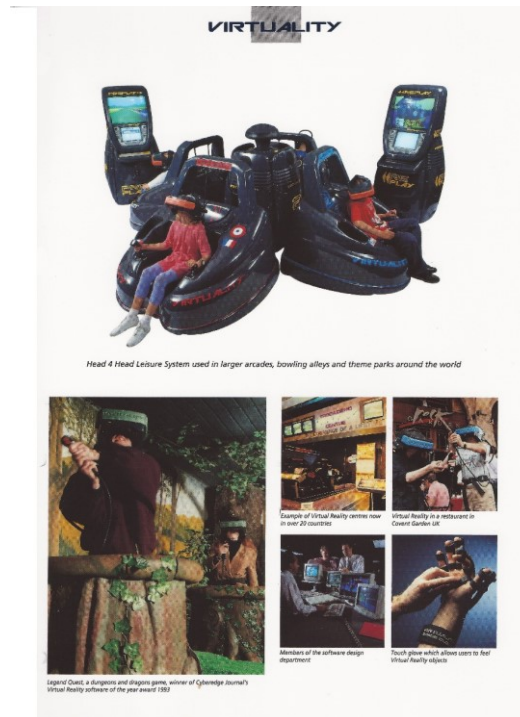


Figure 6 Virtuality marketing campaign in the 90s
(Jonathan D. Waldern, 2014)



Figure 7 The Power Glove by Nintendo (Evan-Amos, 2011)

A Comeback

In 2014, Facebook acquired Oculus VR for \$2 billion. This huge acquisition revitalized the VR industry and started a new wave of investments and research in VR (Jerald, 2015).



Figure 8 Oculus Rift virtual reality system (Wang, 2017)

What's Different?

An obvious question to ask would be: How is VR today different than that in the 90s? What caused this revival besides the capital investments and media coverages? Here are some technological reasons behind it:

- Moore's Law

Over the past two decades, the computational power of CPUs and GPUs has continued to grow. Especially, the performance of GPUs has been growing even faster than CPUs. This allows better graphics capabilities at a much lower price.

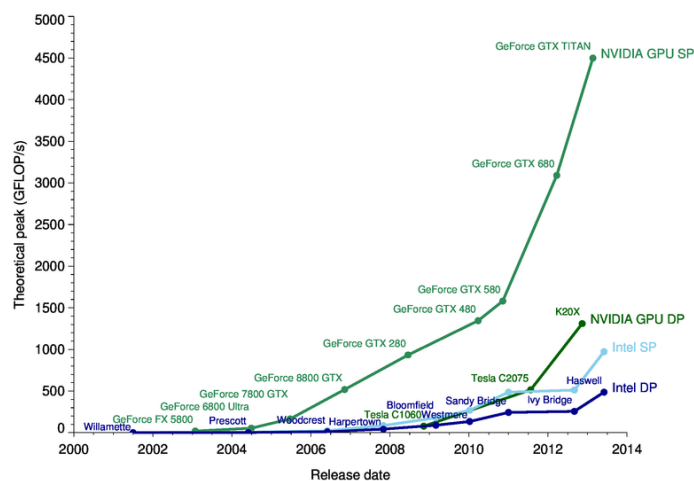


Figure 9 Performance comparisons between CPUs and GPUs (Galloy, 2014)

- Cheaper and Better Display

The OLED screen in Oculus DK2 is actually the same as the Samsung Galaxy Note 3 mobile phone (Welch, 2014). The use of cheap, mass manufactured parts ensures the affordability of VR systems. Additionally, the OLED screen has a larger field of view as well as a lower display latency. Both parameters are critical for delivering a comfortable and immersive VR experience.

- Robust Tracking Technologies

New tracking technologies such as Valve's "Lighthouse" system and Oculus's "Constellation" system bring more robust tracking with less latency into VR. This enables more comfortable VR experiences and richer user interactions.

While it is still controversial about whether Virtual Reality will truly take off this time, one thing has become apparent is that we have reached the point where people stop to question the legitimacy of the reality that is being presented by the virtual system and start to accept and adapt to it.

1.4 An Overview on Tracking Technologies

Why is Tracking Important for VR?

Position and orientation tracking is the foundation of Virtual Reality. It enables the system to react to user's movement in order to render the real-time image they would see in the virtual world. The tracking performance has a great impact on the overall experience in term of comfortability and immersion. Bad tracking tends to cause motion sickness.

There are total six degrees of freedom in tracking, which are translations (X, Y, Z) and rotations (roll, pitch, yaw). Low-end VR systems such as Google Cardboard and Samsung Gear VR can provide orientation-only tracking. While high-end systems such as Oculus Rift and HTC Vive can provide full 6-DOF tracking of user's HMD (Head-mounted display) and controllers.

Inertial Tracking System

An IMU (Inertial Measurement Unit) is an electronic device that measures velocity, orientation, and gravitational forces, using a combination of sensors (accelerometers, gyroscopes and magnetometers)(Yuval Boger, 2014). IMU sensors are widely available nowadays, equipped in almost every mobile phone.

Accelerometers and gyroscopes measure linear acceleration and angular velocity respectively. To get the position, a double integration need to be applied to the linear acceleration. Then a single integration need to be applied to the angular velocity to get the orientation. However, a double integration will introduce a significant drift over time, which makes pure IMU tracking system not suitable for positional tracking. Therefore, IMU tracking is usually combined with external 3-D references such as optical sensors or GPS to correct the drift (Oliver Kreylos, 2014).

Optical Tracking System

Optical tracking involves using cameras to track visual features in order to reconstruct the 3-D pose. Depending on where the camera is placed, optical tracking can be categorized into “outside-in” and “inside-out” methods. In the case of “outside-in” tracking, features are usually on the tracked object consist of artificial markers such as LEDs or reflective markers. In the case of “inside-out” tracking, it can be pure vision-based features such as corners or patterns. Optical tracking is accurate and less susceptible to noise from the environment. But, like any optical technologies, it’s limited by occlusion, which is a big problem when dealing with indoor VR. So, optical tracking is usually combined with IMU tracking to get better results.

“Outside-in” Tracking

“Outside-in” means that the camera is placed at a stationary position and markers are on the tracked object. This is a common method adopted by many products on the market right now. Because it’s more stable and easy to setup.

First, the camera looks for the markers on the tracked object. After extracting the features, we get a 2-D projection image of all 3-D points. Then we can use PnP (Perspective-n-Point) algorithm to estimate the pose (Lepetit, Moreno-Noguer, & Fua, 2009). Here are some of the example systems that use this method:

OptiTrack

OptiTrack is one of the most popular motion capture systems. It’s widely used in game and film industry to capture actor’s performance. It utilizes IR light on the camera, which is reflected off the passive markers, to track an unlimited number of objects in a large volume of space with high accuracy. However, due to the extreme costs, it’s only used by professionals for big budget project.

Oculus Constellation

“Constellation” is the positional tracking system of Oculus VR headset, consisting of an infrared tracking camera and the IR LEDs on the headset. The LEDs are precisely positioned on the headset so that the system can determine its position using 3-D pose reconstruction algorithm. Also, each of the LEDs is flashing in a particular pattern for identification.

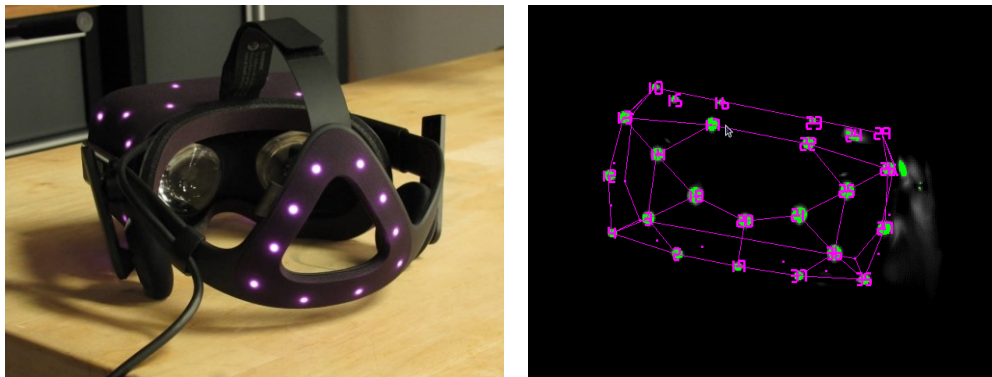


Figure 10 Active IR markers on the headset and its 2-D projection image (IFixit, 2016) (Kreylos, 2014)

HTC Vive Lighthouse

“Lighthouse” is the tracking system for HTC Vive VR headset. The design originates from a prototype called “The Minnesota Scanner” (Sorensen, Donath, Yang, & Starr, 1989) and is further developed by Valve Corp. Instead of using a camera, it uses two laser emitters called “base station” to constantly scan the entire tracking volume (rvdm88, 2015). Moreover, the base station has no communication with any external system, which means the marker is responsible for calculating its own position based on the scan intervals (Allyn Malventano, 2016). This enables the tracking system to be distributed and has many potential applications in indoor positioning and robotics.

In each cycle of 1/60s, the base station will execute the following actions (Kreylos, 2016):

- Emit an omnidirectional flash for start of X scan.
- X-motor rotates to scan the X-axis.
- Flash for start of Y scan.

- Y-motor rotates to scan the Y-axis.

The marker consists of a photodiode and a watchman chip which will register the time of each scan arrival. Then, this can be used to calculate the relative x and y angle to the base station. If we know the relative angles of all the markers, we can construct a virtual image that is resemble to the 2-D projection image of a camera-based tracking system. Therefore, the same 3-D pose reconstruction algorithm such as PnP can be used to calculate the pose. Combined with internal IMU, the system can achieve an update rate over 1000 Hz and latency within 1ms.

Currently, the Lighthouse system is the only tracking technology with both great accuracy and cheap price. Also, Valve is opening this technology to third-party developer. With the TS3633 chip, custom tracked object can be integrated into the Lighthouse system.

“Inside-out” Tracking

“Inside-out” means that the camera is placed on the tracked object such as headset and the markers are placed in stationary locations. Or the marks can be features detected by computer vision algorithm. Then the 3-D reconstruction can be achieved by a process called SLAM (Simultaneous Localization and Mapping). SLAM will not only provide tracked object's position but also the 3-D reconstruction model of the whole environment.

1.5 VR's Role in Design

1.5.1 Visualization and Walkthrough

UE4Arch

This real-time visualization is developed in the Unreal 4 game engine. Users can walk freely in the virtual environment and customize the color of the furniture. The textures and lightings are pre-generated in order to produce the photorealistic effect.



Figure 11 Photorealistic architecture walkthrough
("UE4Arch - Lake House Real-time Archviz," 2016)

IrisVR

IrisVR is a tool that converts models from modelling software such as Rhino, SketchUp and Revit, directly into VR for visualization and walkthrough. Hence, designers can experience and inspect their designs prior constructions.

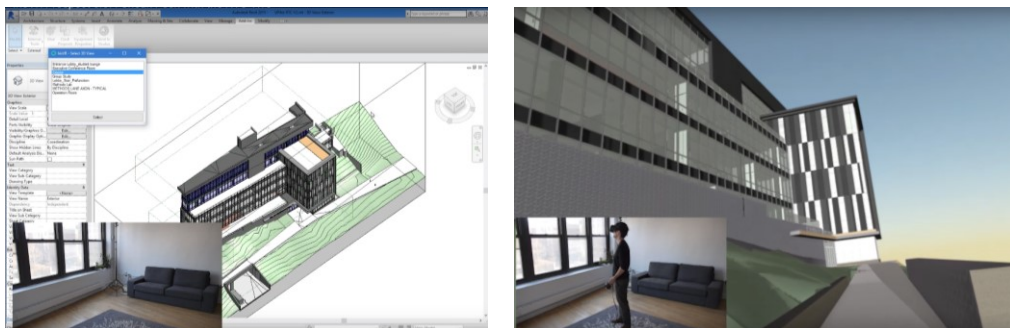


Figure 12 VR walkthrough of a Revit model
("IrisVR Prospect 0.3.4 Sneak Peek with the HTC Vive," 2016)

1.5.2 Collaboration

Modelo

Modelo is a web-based 3-D collaboration tool for designers. Designers can make annotations and sketches in the 3-D models and share them among coworkers.

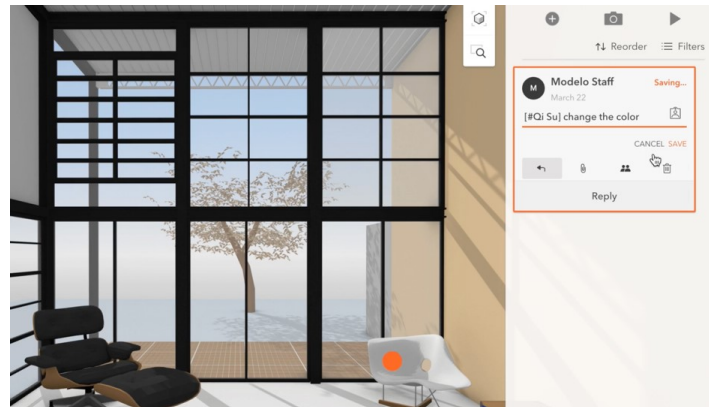


Figure 13 Online 3-D collaborations
("Markup CAD designs in the browser," 2017)

Bigscreen VR

Bigscreen VR is a program that maps the Windows desktop onto a virtual screen in VR. Users appear in VR as avatars that can talk and draw. So, designer from different places around the world can be connected via Bigscreen and host remote conferences.



Figure 14 Remote conference in VR
("Bigscreen VR Desktop Trailer," 2016)

1.5.3 Creating 3-D Contents

Tilt Brush

Tilt Brush allows users to draw freeform sketches in space. Users use two controllers to paint. One controller acts as the “paint brush”. The other one is the “palette” for choosing the color and shape of the “paint brush”.

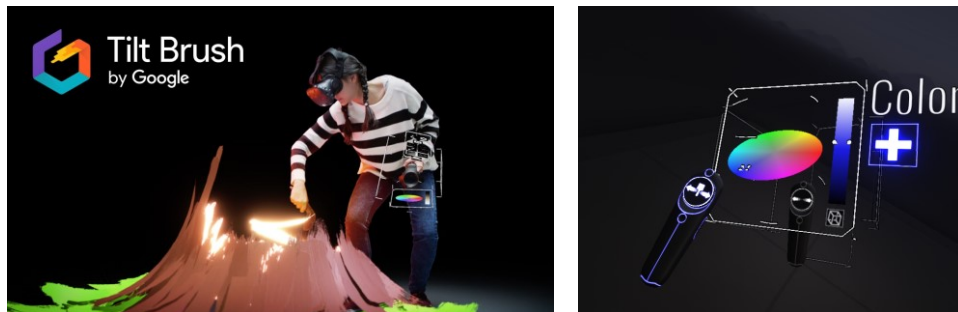


Figure 15 Drawing sketches in space with color palette
 (“Tilt Brush: Painting from a new perspective,” 2016) (Machkovech, 2016)

Leap Motion

The Leap Motion controller is a hand tracking device based on computer vision technologies. The device can be mounted to the front face of a VR to track the positions of user’s hands and fingers. Then the virtual “hands” can be used to interact with virtual interfaces.



Figure 16 Hand tracking with Leap Motion controller
 (Leap Motion, 2016) (“Leap Motion: Orion,” 2016)

From the examples above, we can conclude that Virtual Reality is very effective in creating immersive and interactive experiences. Furthermore, designers have an accurate sense of scale as well as depth perception in VR (Jerald, 2015). This is particularly important for spatial design. Meanwhile, more novel input methods such as eye tracking (FOVE, 2017) and voice recognition are on the horizon, which will substantially enrich the types of interactions in VR.

1.6 Research Question

Virtual Reality has been proven as an effective visualization tool. But can we push its boundary further than just being an immersive display? Can we make Virtual Reality a true design medium for designers? How should we design it to be more intuitive and expressive? And what's the implication of using such medium on the field of computer-aided design? The aim of this thesis is to answer these questions by bridging the gap between the physical and the virtual world and exploring the new design possibilities this medium unlocks.

2 Related Work

2.1 CityScope

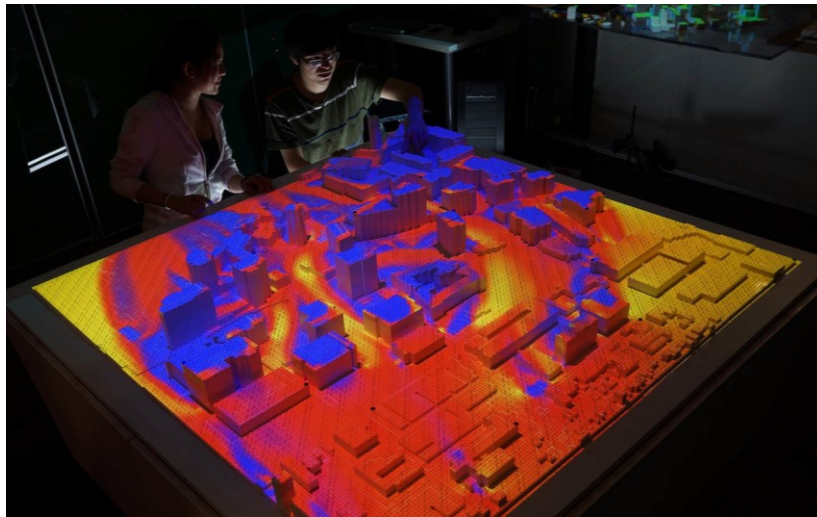


Figure 17 Wind flow simulation (WINDER, 2014)

CityScope was developed by the City Science Initiative at MIT Media Lab as an urban design and analysis tool (Businaro, 2016). A projection system projects dynamic information onto a physical model made of Lego bricks. Users can physical move the bricks to simulate a different scenario. In spite of the high-fidelity physical models and rich visual information, the system is restricted by the types of physical models it can augment. For example, if the user want to view information about a different place or view it at a different scale, then the whole model needs to be rebuild. With Virtual Reality, users can view the models without any physical constrains. However, it poses a new challenge on providing haptic feedback for arbitrary models.

2.2 The reacTable

The reacTable is an interactive music instrument with a tabletop tangible user interface (Jordà, Kaltenbrunner, Geiger, & Alonso, 2006). It uses a camera inside the table to identify and track the objects on the translucent table surface. The objects were treated as different parts of the audio

synthesizer so that users can produce music by moving them around and making new connections. By placing the tracking camera underneath the table, the system avoids the occlusion problem with downward cameras caused by users' moving hands. But it limits the user interactions to the near-surface area. In contrast to CityScope, this project has a low-fidelity interface using cubes rather than a detailed model, which provides more flexibilities in terms of user interactions.



Figure 18 The reacTable at the Altman Center (Williams, 2007)

2.3 Bricks

In this project, the authors explored the concept of “Graspable User Interface” (Fitzmaurice, Ishii, & Buxton, 1995). Users can use a physical object called “brick” to manipulate a virtual 2-D object on the surface screen. And by “graspable”, it means that the virtual object can be “grasped” by attaching the physical object directly on top of it. The system is able to track the x and y positions and the rotation of the “brick”. Thus, users can move or rotate the “brick” to place the virtual object accordingly. Multiple “bricks” can be used together to accomplish more complex tasks such as generating a spline curve. It would be interesting to explore how this concept can be extended into 3-D space. Will 6-DOF tracking of the physical object enable new forms of interactions?

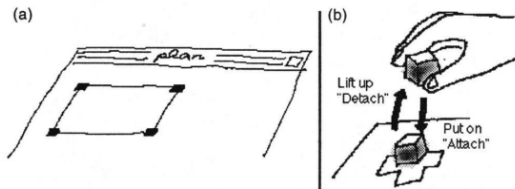


Figure 2. (a) Traditional MacDraw-like application which uses electronic handles to indicate a selection. (b) Selecting using a brick.

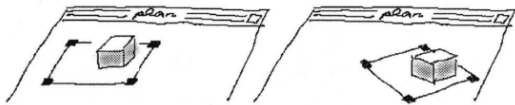


Figure 3. Move and rotate virtual object by manipulating physical brick which acts as a handle.

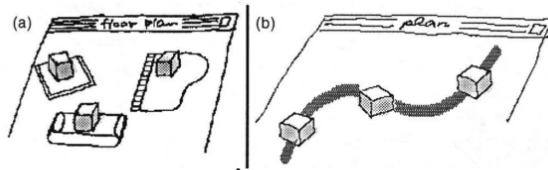


Figure 5. (a) Proposed simple floor planner application. (b) Many physical bricks are used for specifying multiple control points for creating a spline curve.

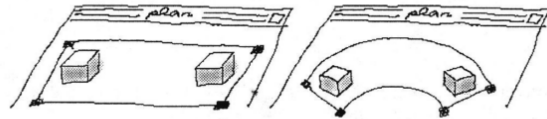


Figure 6. Moving and rotating both bricks at the same time causes the electronic object to be transformed.

Figure 19 Moving or rotating the “brick” to manipulate the virtual shape
(Fitzmaurice et al., 1995)

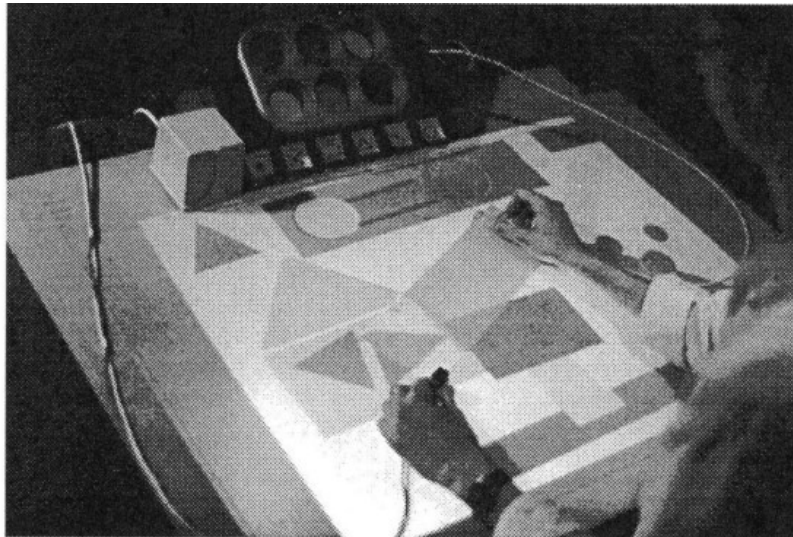


Figure 8. GraspDraw application and ActiveDesk.

Figure 20 A drawing system based on two hand interactions (Fitzmaurice et al., 1995)

3 Hypothesis

My hypothesis is that, through the physical embodiment of the design interfaces, Virtual Reality can become more intuitive and expressive as a spatial design medium. By creating a tangible user interface that is highly responsive to user's inputs, the system can potentially augment the virtual experience and increase the affordances of the virtual interface.

On the other hand, a physical object is inherently haptic. The sense of touch is tightly coupled with our vision and hearing to form a feedback loop that supports our daily actions (MacLean, 2008). Therefore, haptic feedback is crucial for designers to perceive and explore their works. When performing task that requires craftsmanship or expertise, designers rely heavily on haptic feedback such as shape, weight and texture. It brings intimacy between the designer and the object by engaging them in a personal conversation. Thus, the haptic feedback from the interface can greatly increase designers' sense of presence in VR and provide them with more direct controls over the virtual objects.

4 Methods

A prototype was developed to test the hypothesis. During the process, design decisions were made with the goal of creating an intuitive and expressive experience for designers.

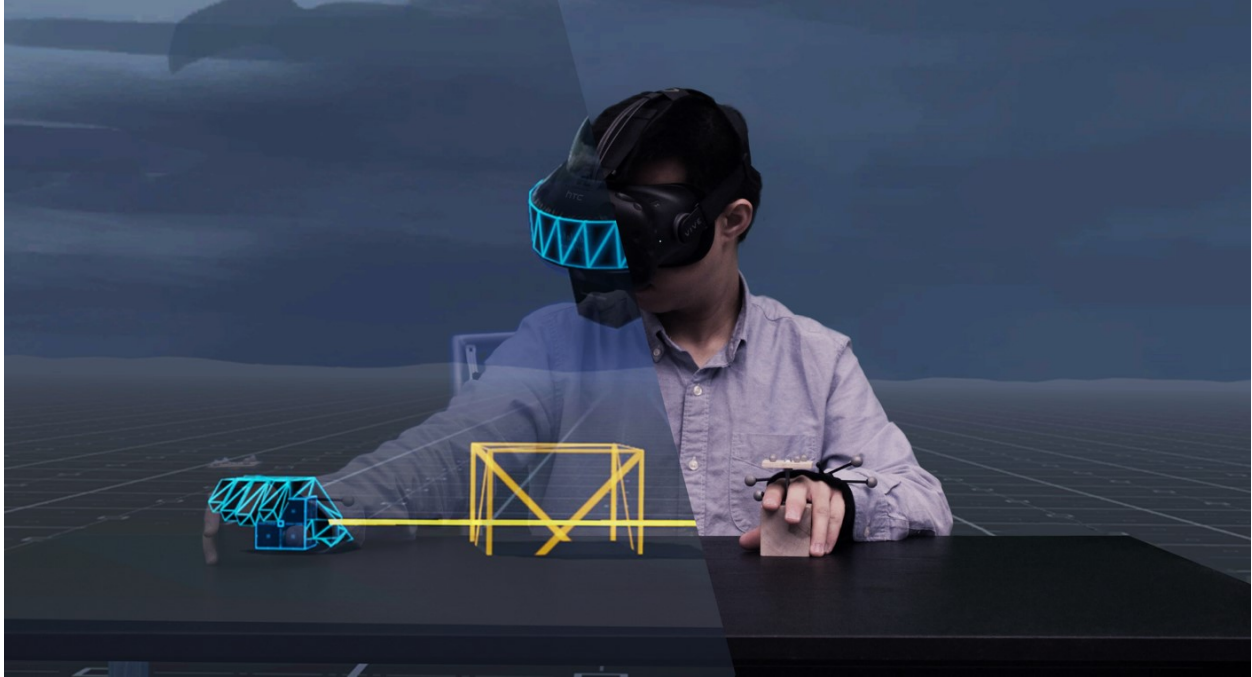


Figure 21 Mixed reality capture of project HADEN

4.1 Design Decisions

4.1.1 Overlapping Real and Virtual Objects

The passive haptic feedback is generated by overlapping real and virtual objects using OptiTrack tracking system. Retroreflective markers are attached to real-world objects so that the tracking system can calculate their positions and orientations. Then the virtual objects in VR are mapped to corresponding real-world objects with a 1:1 scale. The objects being tracked in real-world are:

- Two gloves, one for each hand
- One wooden cube
- One 3-D printed cube

The wooden cube has the exact same size as the virtual cube. The 3-D printed cube has a different form factor. This is to test whether the user can accept the discrepancy between the real and virtual objects. Although the real-world desk is not being tracked, there is still a corresponding virtual desk in VR. This is possible because both Lighthouse and OptiTrack system are using the center point of the desk as their origin point. In this way, the position of the desk effectively becomes known even though it is not being actively tracked.

4.1.2 Designing for Seated Experience

Instead of designing a standing VR experience, the system's default design is for seated experience. There are several reasons for this decision:

- Designers usually work in a seated environment such as an office or a studio.
- When being stationary, a user is less likely to experience motion sickness.
- Apart from being seated, users do not need to hold the controllers continuously. Instead, the controllers can be placed on the table at any time. This enables the user to use the system for a longer period of time without being fatigued.
- By keeping the interfaces within user's arm reach, the interactions can be more accurate and efficient.

4.1.3 Spatializing Controls to Reduce Cognitive Load

Given the analysis in previous chapter, we can conclude that the current CAD interfaces are overloaded with functionalities. Users have to memorize where to access their tools beneath layers of menus. With the intention of reducing the cognitive load for users, the system spatializes the controls into two cubes and one button, adopting the metaphor of a real-world workspace with interfaces of high affordance, which facilitates the use of users' spatial memory.

4.1.4 Centered Cursor for Improved Accuracy

The cursor that indicates the location of the generated cube situates at the midpoint between the two controllers. This method reduces the noise from user's hand movements and improves the accuracy of cube placement.

4.1.5 Physical and Virtual Confirmation

A confirmation mechanism is required for creating and erasing the cubes. For creating the cubes, a physical button is used on one of the controllers. The button is connected to a circuit that transmits wirelessly to the system via Bluetooth. If the button is pressed once, it will create one cube. If the button is held down, it will create cubes continuously. For erasing the cube, a virtual button on the table is used. Since user's hands are being tracked, the virtual button can be pressed if user reaches out to it and presses against the desk. Although there is no physical button, the passive haptic feedback from the table makes this interaction believable. According to one of the tests, it's even more convincing if there is a foam pad on the real-world table overlapping with the virtual button.

4.1.6 Gestural Controls over Position, Scale and Rotation

Users can control the position, scale and rotation of the generated cube at the same time. This design resembles the pan, pinch, zoom and rotate gestures on the touch screen. In here, these gestures were generalized and extended into 3-D space. This coupled interaction makes it intuitive and efficient for users to generate cubes.

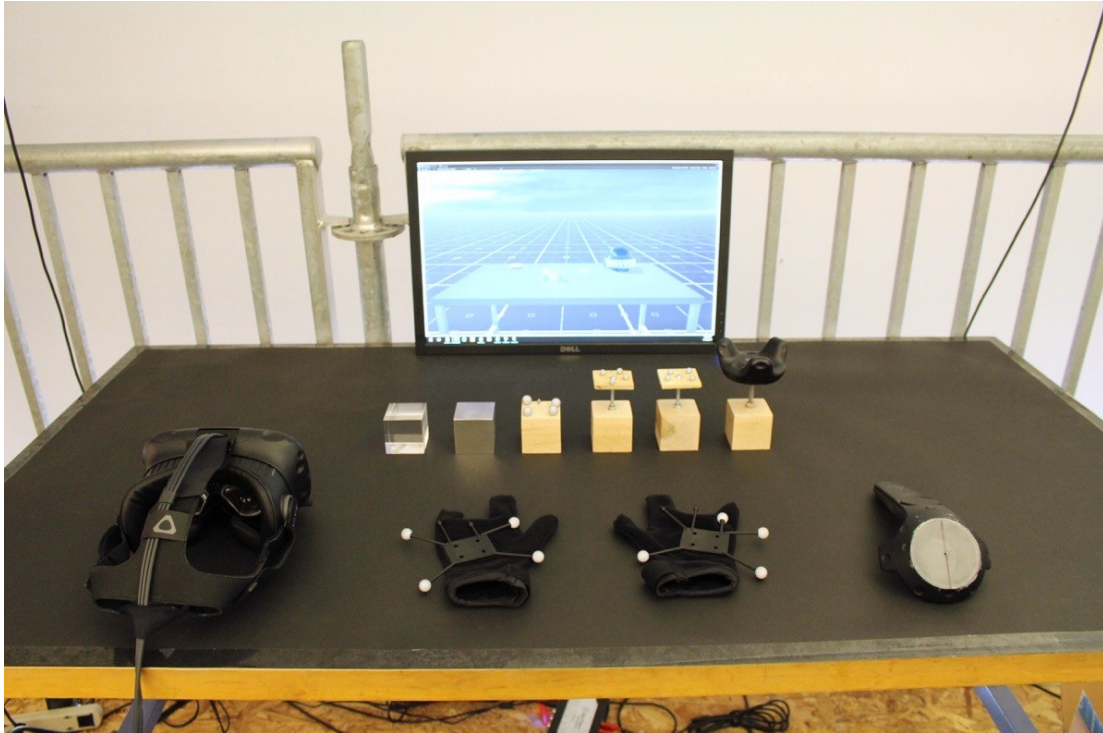


Figure 22 Retroreflective markers for hand tracking and object tracking

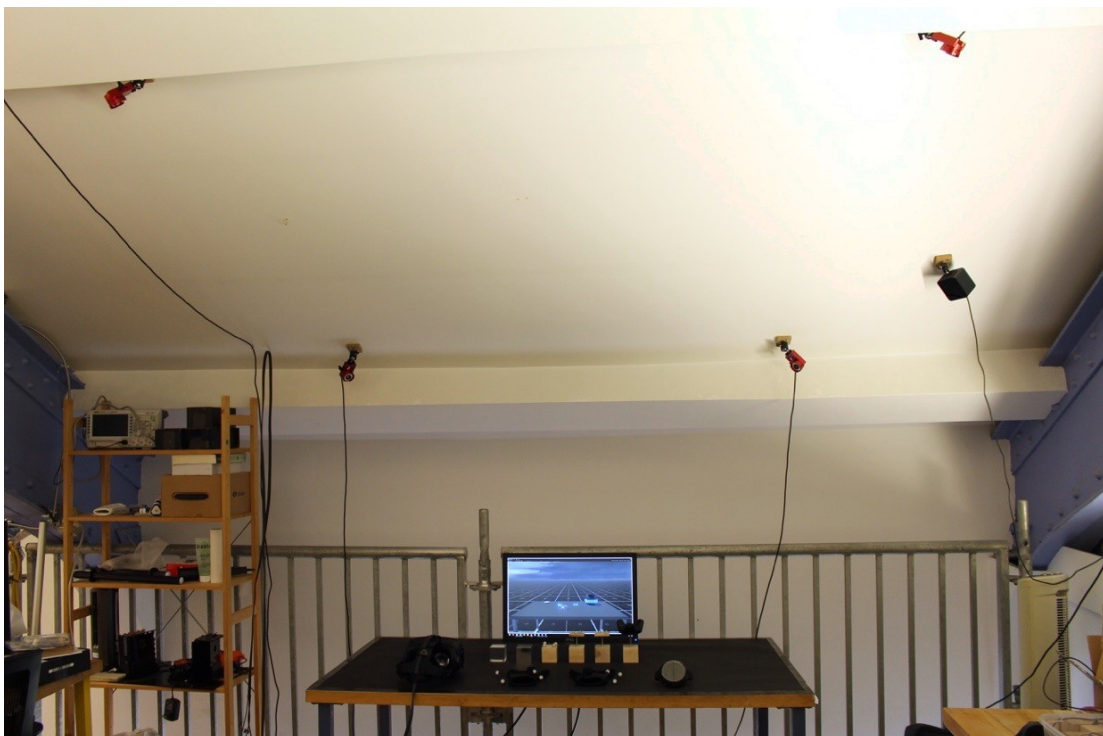


Figure 23 Project setup



Figure 24 Clicking the button on the controller

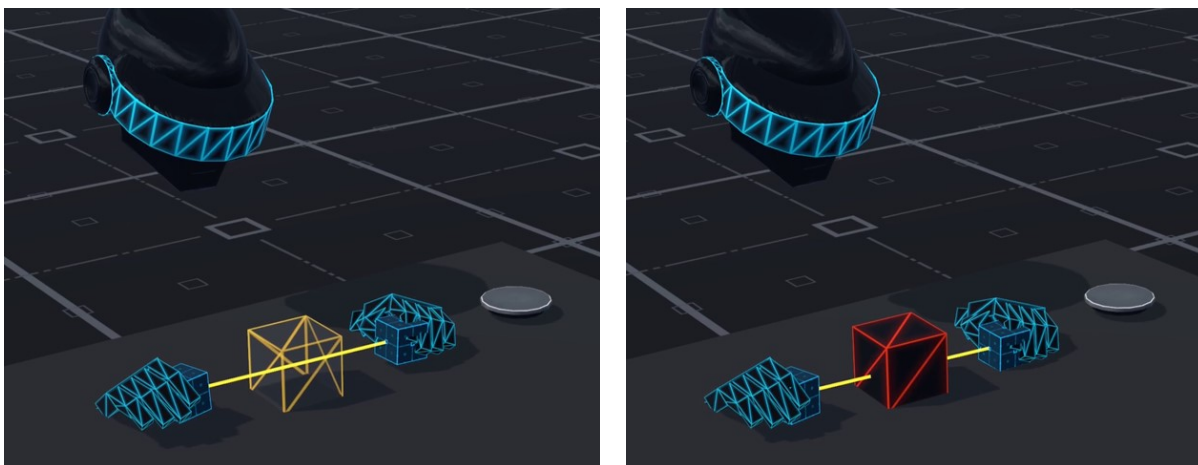


Figure 25 Creating a cube by clicking the physical button

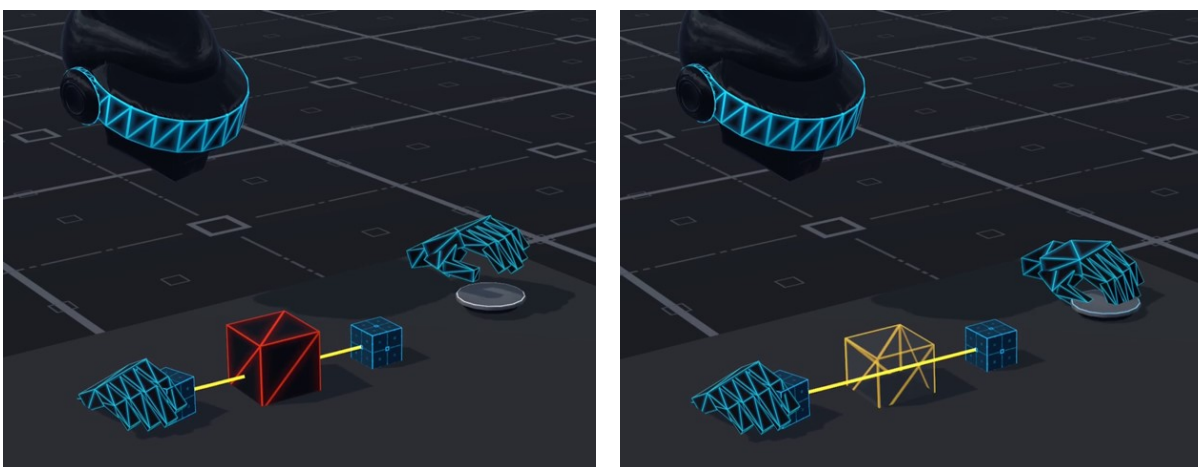


Figure 26 Erasing the cube by pressing the virtual button

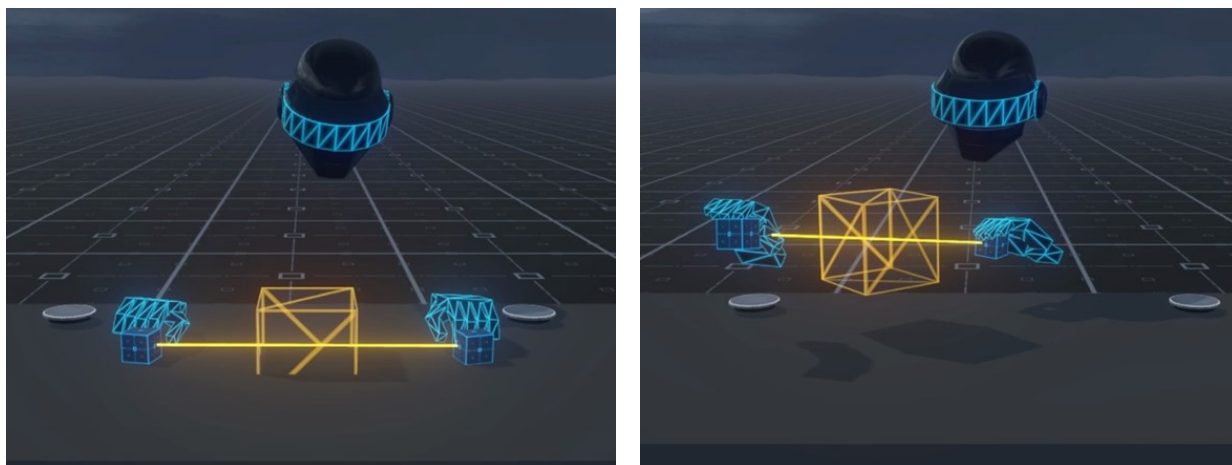


Figure 27 Centered cursor between two controllers

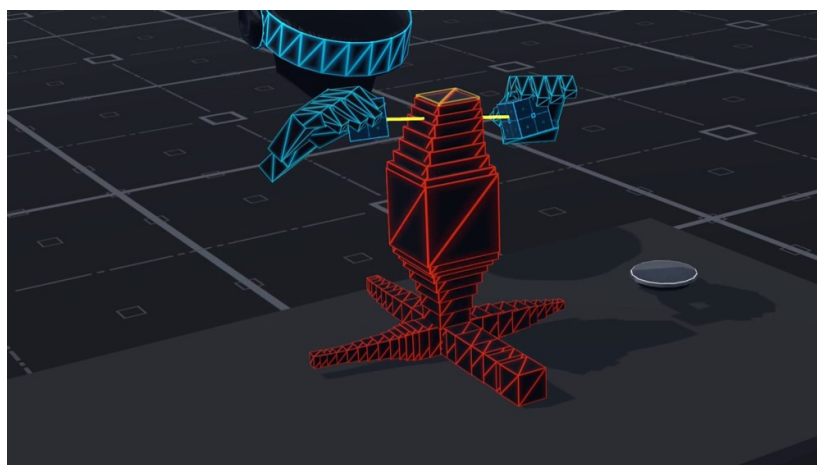


Figure 28 Changing position and scale at the same time

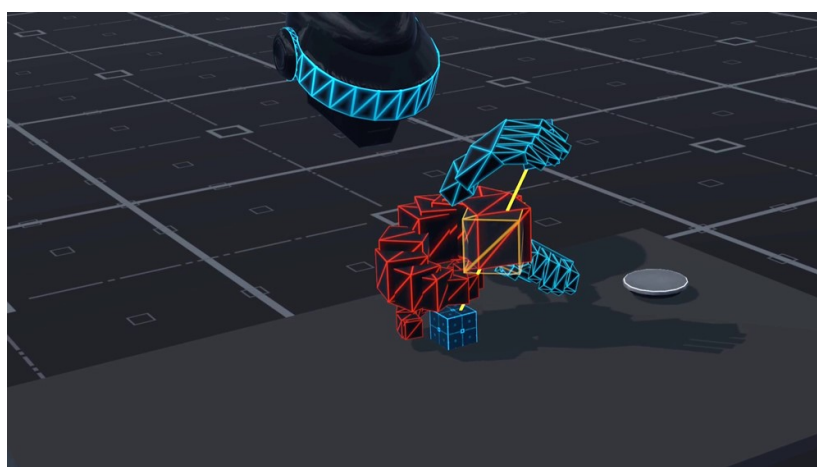


Figure 29 Changing position and rotation at the same time

4.2 Technical Details

Software

- Unity 5.6.0 f3 (64-bit): Game development engine.
- Motive 1.10.2 Final: Motion tracking software with OptiTrack.

Unity Plugins

- SteamVR: for Vive headset support in Unity.
- OptiTrack Unity Plugin 1.01: for receiving positional data from Motive.
- SerialComm¹: for receiving serial data from the Bluetooth controller.

This prototype was developed in Unity and programmed in C#. It uses Motive to transmit the positional data from OptiTrack directly into Unity. It also relies on an open-source framework, VRUX (Scott, Crawford, & Wang, 2017). This framework features an event-driven architecture, which makes the development much easier and flexible.

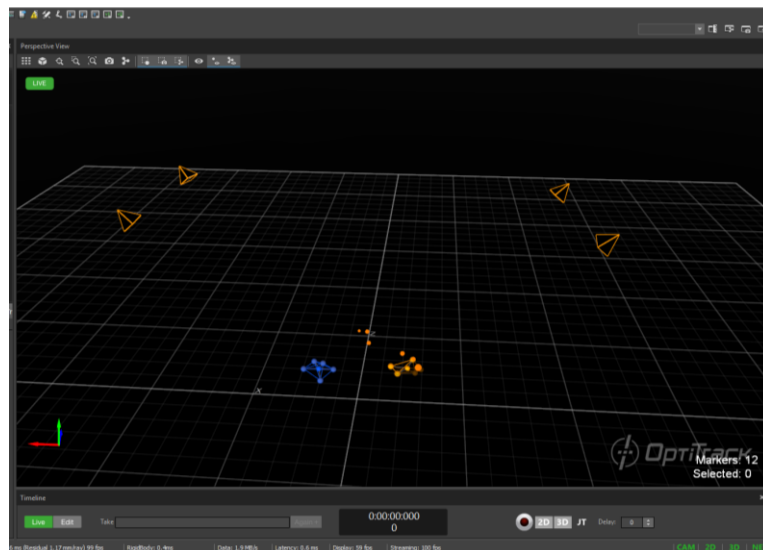


Figure 30 Motive motion tracking software

¹ <https://github.com/DWilches/SerialCommUnity>

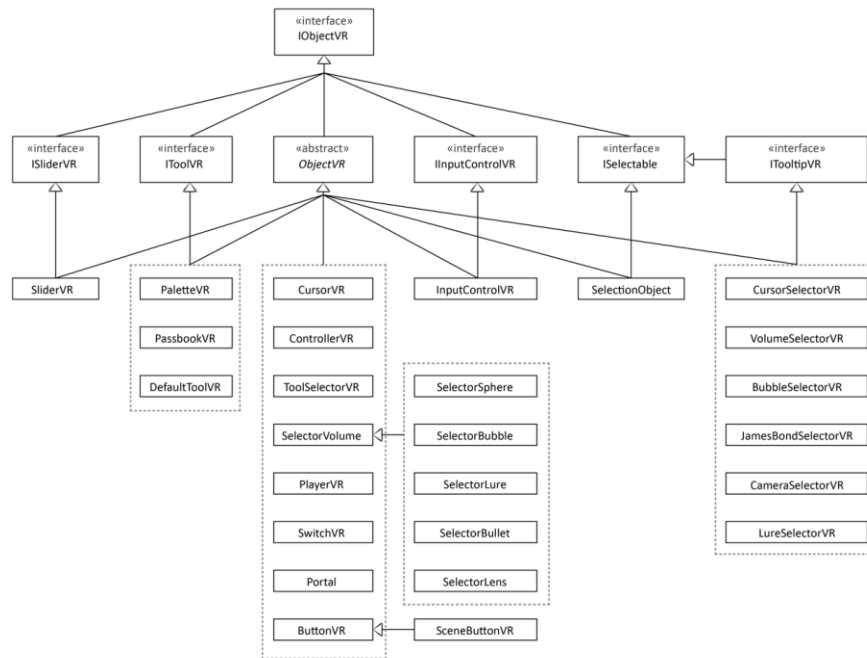


Figure 31 Class diagram for VRUX framework

Tracking System Selection

- HTC Vive Lighthouse Base Station x1
- OptiTrack Flex 3 Tracking Camera x4

To provide the passive haptic feedback, the system uses both Lighthouse and OptiTrack system for object tracking. The reason for choosing OptiTrack is because of its high accuracy and low latency in tracking. Also, the test environment is relatively controlled so occlusion will not be a serious issue.

Iterations of the Controller

In the first version of the controller, the retroreflective dots are directly mounted on top of the wooden cube. This causes tracking problems when user's hand is covering the top. In the second version, markers are mounted on an elevated platform which allows the user to place their hand underneath it.

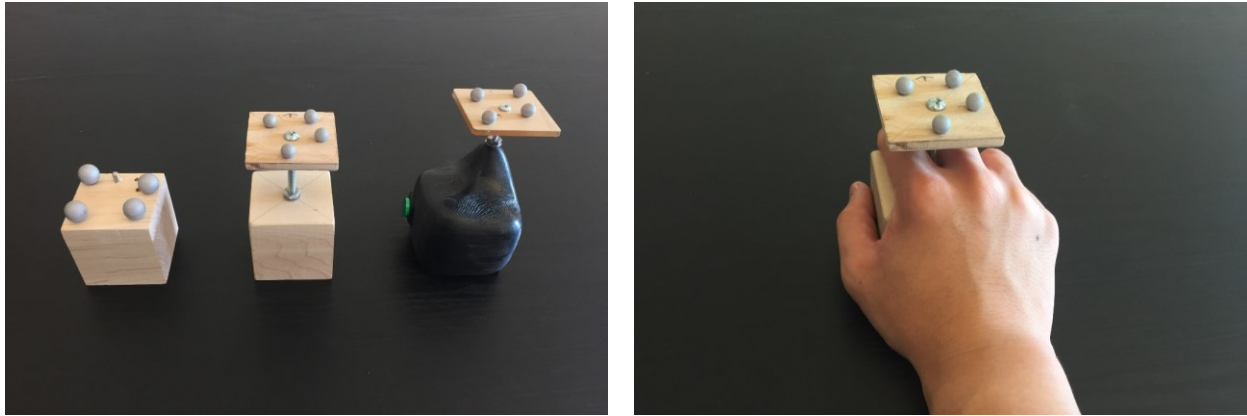


Figure 32 Three iterations of controllers

Calibration

One of the biggest challenges of this project is to accurately overlap the OptiTrack and Lighthouse system so that a single tracked object has the same positional readings across two systems. OptiTrack comes with a component called “calibration square”, which is used for defining an arbitrary point and orientation in real-world as the origin point and orientation of the system. Yet, the Lighthouse system doesn’t have such “calibration square” to define its origin. The solution is to use one of the Vive controllers as the “calibration square” for Lighthouse, mapping the system origin to the center point of the controller’s upper ring. The following is the calibration process:

- Define an origin point that will be shared by both systems, in this case, the center point of the desk.
- Mount four OptiTrack cameras above the four corners of the desk.
- Adjust cameras’ heights and orientations to maximize the coverage area within user’s arm length over the desk.
- After a full calibration of OptiTrack, align its ground plane to the pre-defined origin point.
- In Unity, align the Lighthouse system (CameraRig) with the origin in run time.
- After aligning both systems with the origin, they will be accurately overlapped.



Figure 33 Aligning two systems with the center point of the desk



Figure 34 “Calibration square” with custom center point



Figure 35 The calibration views from four different OptiTrack cameras

Physical Prototyping

The Bluetooth controller includes the following components:

- Adafruit Pro Trinket - 5V 16MHz
- Illuminated Momentary Pushbutton
- HC-05 Bluetooth Module
- Lithium Ion Polymer Battery - 3.7v 500mAh

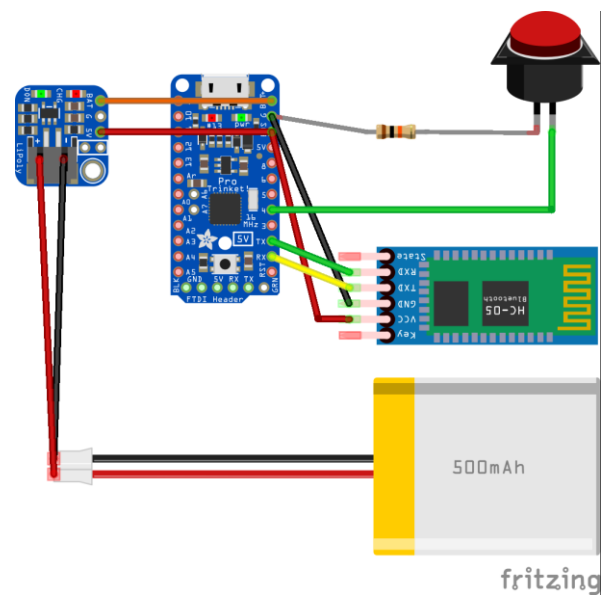


Figure 36 Circuit wiring diagram

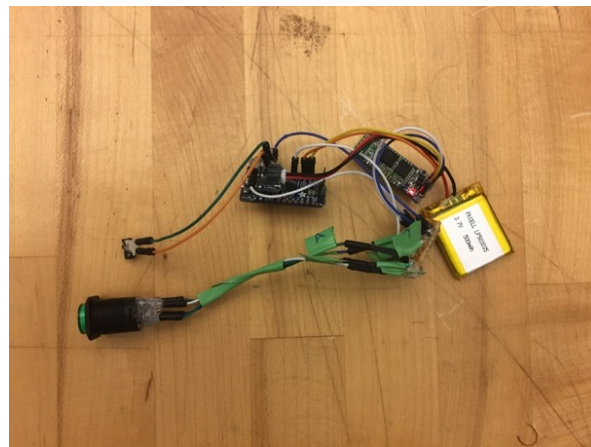


Figure 37 Circuit inside the controller

5 Discussion

The system was installed in a gallery and demonstrated to the public. Both users that are familiar with Virtual Reality and those have little or no prior experience with such system tried the demo.

And here are some observations from the demonstration:

- Users were instructed on how to hold the controllers and press the button to generate and erase the cubes. No other instructions were given.
- Most users quickly learned the controls and could freely generate cubes with different scales and rotations even though there is no explicit instruction telling them how to do so. This proves the interaction design is intuitive and effective.
- Some users were able to come up with unique designs such as a character or a temple. This shows the system is expressive enough for designers to be creative and imaginative.
- When generating large number of cubes or cubes of large sizes, the cubes will block user's field of view, making it difficult to draw more or erase them. This could be solved by putting constraints on the size of the cube or limiting the region where user can generate cubes. Another solution could be adding controls that scale and rotate all the cubes generated so that the user can observe the design from multiple scales and angles.
- Even though the users were instructed on how to hold the controllers, after they put on the headset, it became hard for them to reach out to the controllers without touching the markers on top of the cube. Since the visual representation in VR doesn't show the top marker, they can immediately notice the discrepancy. This indicates that the placement of the markers could be improved or there should be some visual cues to guide the users on how to grab the controllers.



Figure 38 Live demonstration at the gallery

6 Conclusion

6.1 Contributions

This thesis sets out to discover an expressive medium for designers to focus on creative and imaginative spatial designs. Through the process of conducting research on previous works, identifying the problems, raising hypotheses, building prototypes and observing, this research explored a new approach to design and presented a new relationship between designer and design system. Here are some of the major contributions of this thesis:

- Implemented a system that is intuitive and expressive as a spatial design medium.
- Incorporated passive haptic feedback into VR by overlapping physical and virtual objects.
- Developed a quick calibration method to overlap Lighthouse and OptiTrack tracking systems.
- Built a custom wireless controller that is capable of triggering events in VRUX framework.

6.2 Limitations

Occlusion

Due to the optical nature of the tracking systems, Lighthouse and OptiTrack are both limited by the problem of occlusion. OptiTrack is more sensitive to the line of sight with the markers since it's using pure optical data to determine their positions. The markers must be visible to at least two cameras at any given time to establish tracking. So, it requires the marker to be placed on top which limits the usability of the system. This also suggests a thorough calibration is required to achieve the best results. Lighthouse is more robust because of its larger field of view and high number of light receivers on the tracked objects. Combined with IMU data, Lighthouse can continue tracking when receivers are partially occluded. However, significant drift will occur when the tracked object is mostly or even completely occluded.

Finger Tracking

Neither of the tracking systems has the capability to track fingers (A more advanced model of OptiTrack system supports finger tracking). While user's hands are being tracked by OptiTrack in VR, their fingers stay in a fixed position relative to the hands which may seem disconcerting to some users. Besides, the lack of finger tracking limits the granularity of the interactions. During the process of prototyping, a finger tracking device called Leap Motion was tested. Though its tracking was very unstable due to interference with OptiTrack system.

Haptic Feedback for Dynamic Contents

The system utilizes passive haptic feedback from the tangible user interface. One of the limitations of this method is the difficulty of providing haptic feedback for dynamic contents that user generates. The limitation originates from two aspects. First, it is difficult to align the existing physical objects with the virtual contents to provide the passive haptics. Second, the discrepancy between the passive haptics and the visual representations is hard to control or compensate.

6.3 Next Steps

Continue Development

This project is still under development. The next steps would be iterating the design based on the observations and feedback from the demonstration and adding more functionalities. Here are some of the features to be modified or implemented:

- Improve the design of the controllers to avoid users accidentally touching the markers.
- Add controls on the overall scale and rotation of the generated cubes.
- Add more primitive shapes other than cubes.
- Add spatial menu system for selecting different primitives.

Custom Lighthouse Tracking

The system consists of both Lighthouse and OptiTrack system. This complicates the tracking process and increases the overall cost. Recently, Valve has release a custom Lighthouse sensor for positional tracking. In addition to the sensor, HTC released a Lighthouse tracker that can be attached to other objects. The custom sensor and tracker open up the possibilities of tracking arbitrary objects within the Lighthouse system, which can be used to provide the passive haptic feedback. Furthermore, if the system only uses Lighthouse tracking system, it would be possible to integrate the finger tracking from Leap Motion since there is no interference between Leap Motion and Lighthouse system.

User Study and Evaluation

A more formal and rigorous user study is needed to test and evaluate the effectiveness of the design decisions. Tests should be carried out on both normal VR system without haptic feedback and system that integrates the tangible user interface in order to gain further insights on the implications of using this system and the effects it has on designers' creativity and design thinking.

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