Electronic Textiles as Tangible Interface for Virtual Reality

by

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A thesis exhibition presented to OCAD University in partial fulfillment of the requirements for the degree of

Master of Design

in

Digital Futures

OCAD University Open Space Gallery, April 12-15, 2018

Toronto, Ontario, Canada, April, 2018

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Abstract

This project investigates the development of a series of experimental, tangible, electronic textile (e-textile) interfaces to virtual reality (VR), using the approach of human-computer interaction (HCI). The e-textile interface is an unconventional controller that manipulates objects (3D visual asset) within virtual reality. This research has been framed within the context of HCI using a framework of Tangible User Interfaces (Ulmer and Ishii 2000).

Through this research I explore how human touch relates to tangible objects and passive haptics. I also explore the overlap between visual experience and virtual reality by employing the theory of Haptic-Visual overlap (Fitzmaurice 1998), which deals with 3D volumetric perception of a physical object as well as the idea of Active Touch (Gibson 1962, Lederman and Klatzky 2009, Visell et al. 2016).

Using the aforementioned theoretical frameworks and employing research through design methodology, I prototyped a series of explorative e-textile interfaces and virtual reality digital counterparts.

Acknowledgment

Thank you to my advisors, Kate Hartman and Dr. Emma Westecott, for guiding me through the thesis process.

James Essex and Hector Garcia, thank you for generously teaching me Unity 3D. Your expert guidance about such a powerful coding/software platform, made this thesis possible.

My sincere thanks to Reza at the student workshop at 205 Richmond St. and also the team at the Rapid Prototyping Lab at 100 McCaul for helping create my final prototype. Special thanks to Afaq Ahmed for showing me the Illustrator tools I needed and Anna Cox for proof reading my paper. Finally, thank you to Hammadullah Syed for helping film my video. Your innovative exploration and interaction with my Boomerang prototype gave it a whole new life!

Dedication

To Uday and Mridula

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1. Introduction

This research project investigates the development of an experimental, tangible, electronic textile (e-textile) interface for virtual reality (VR), using a human-computer interaction (HCI) approach. The e-textile interface developed in this thesis is an unconventional controller for a 3D visual asset that is composed of a real world physical haptic interface that is rendered within virtual reality. The e-textile interfaces have been created in two methods. One method embeds sensors in textiles while the other method involves sensors created from conductive and resistive textile materials and fabrics. The sensors capture participant data as they explore the tangibility of the electronic textile interface. The data generated by the sensors is modifies the 3D visual asset within the virtual reality space. The central goal of this thesis is to explore the relationship between tangible objects in the physical world and their corresponding digital representation in virtual reality.

Humans have an age-old relationship with fabrics based on their use in garments, which can be metaphorically understood as a second skin because they are so deeply integrated in daily life. Our interaction with fabric is incredibly intuitive. In this thesis, e-textiles are considered as 'interfaces', particularly in the sense that their unique materiality provides a set of affordances that we can explore and interact with intuitively. Such affordances have been used to develop a soft and deformable tactile interface for a virtual reality experience.

The physical interaction between the e-textile interfaces and digital objects in virtual reality (i.e. VR assets) has been designed using the following theoretical frameworks: Tangible User Interfaces by Umber and Ishii (2000), Theory of Active Touch (Gibson 1962, Visell et al. 2016), and the Theory of Haptic Visual overlap by Fitzmaurice (1998). These theoretical frameworks are discussed in Chapter 2 and refined using the design methodology of Research through Design as discussed in Chapters 6 and 7.

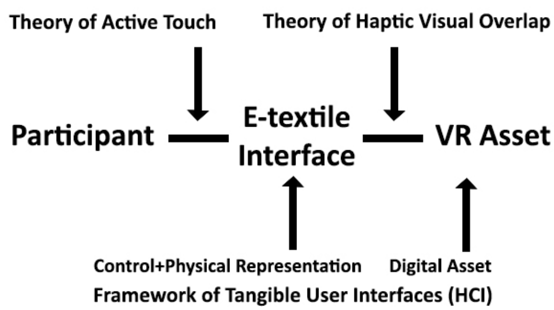

Fig.1 Theoretical Framework for this research

The application of this methodology helped create 3D visual assets in virtual reality and also helped develop the e-textile interface by gathering feedback and the practice of iterative design. Throughout the design process, I intended to develop and create intuitive connections and interactions between the physical and the virtual environments.

Feedback received during the Research through Design phase of this study, was used to develop an interactive and exploratory exhibition piece where users could bridge the gap between the physical and virtual worlds. The Theory of Active Touch (Chapter 2.2) emphasizes the use of textural affordances as a powerful factor in the development of interfaces for virtual worlds. This theory states that the active exploration of materials (i.e. e-textile interfaces) tends to guide the observer's attention to properties of the virtual environment and the corresponding virtual assets found within it. The Theory of Haptic-Visual Overlap, discussed in Chapter 2.3, describes how 3D tangible interfaces in virtual reality compensate for the lack of depth perception while at the same time improving interaction within these spaces. The sense of touch, also referred to as haptics, is known to positively impact task performance within these virtual reality environments. This phenomenon has been reviewed in scientific journals concerned with how the human brain integrates tactile and visual information through 3D volumetric perception (Bouguila, Ishii, Sato 2001) and also by research in the field of haptic integration in virtual reality systems (Insko 2001).

1.1. Background and context of the problem

Currently, virtual reality is predominately accessed through mainstream commercial plastic controllers that provide force feedback (i.e., mechanically generated vibrations from a motor) meant to enhance haptic integration. Force feedback is mainly used during the manipulation of 3D virtual visual assets. For example, when a participant grasps an object and changes the position or orientation of an object in virtual reality, they use a handheld plastic controller. These controllers can be made to point at 3D virtual assets in order to manipulate them with the help of virtual- and controller-based affordances that lead to specific interactions in the virtual world. In this kind of an interaction, the participant has no sense of physically grasping the virtual asset as they are interacting with an abstracted plastic controller. This leads to a lack of meaningful and intuitive haptic sensory integration within virtual reality spaces.

Textiles are materials that we haptically experience every day, both within our environment and on our bodies and Due to their widespread and daily use, we interface with them intuitively. Textile materials are often stretchable and provide some unique manipulations, that when combined with electronics, can create soft and flexible computationally enhanced entities. The interfaces in this thesis are created using e-textiles and, unlike standard electronics, are not built on rigid plastic structures like conventional controllers for virtual reality.

A computing interface is the means of communication between the computer and the user. This is normally a peripheral device such as monitor or a keyboard. An interface is a shared boundary across which two or more separate components of computer system that exchange information. (Blaauw and Brooks 1997) This project uses e-textiles as an expressive haptic inclusion method to virtual reality. By using deformable materials I hope to enhance the relationship between physical interaction and the 3D virtual visual asset.

1.2. Purpose of the Thesis Research

Currently virtual reality spaces suffer from a lack of diversity in tactile and haptic interactions. Physical interactions in these spaces are mainly through hand held plastic controllers, which feature buttons and force feedback cues (i.e. vibration). This project attempts to establish a connection between the user and the virtual space through haptic interference by the addition of soft touch based interfaces that act as controllers to virtual objects (3D visual assets) in virtual reality.

This project attempts to bring the framework and theories from Tangible User Interfaces, Active Touch, and the Haptic-Visual overlap into the domain of e-textile interface design and the design of their corresponding 3D visual assets for virtual reality. This is done by applying the considerations set by these theories in creating explorative e-textiles with designed affordances and tangible qualities, which can act as an interface for interacting with 3D visual virtual assets through touch. Sense integration through touch is a means of non-verbal communication within this medium (Fitzmaurice 1998). Textiles have a propensity to be texturized, are legible to human touch, and encourage active touch (Gibson 1962, Visell et al. 2016), and this project takes advantage of these attributes in order to explore and demonstrate new methods for developing tangible interfaces for virtual reality experiences.

The prototypes created in this project are composed of various tangible e-textile objects that have different stiffness or flexibility and can be physically deformed by hand. The final outcome of this project is a table upon which these physical objects are placed. When participants manually interact with the objects on the table, there is a corresponding manipulation of 3D assets in virtual reality. In this exploration, the material's stiffness or flexibility is correlated to the visually represented 3D virtual assets. Their deformation in virtual space is designed to correspond with the characteristics of their associated physical materials (Ullmer and

Ishii, 2000). Through this relationship, embodiment, and coupling of the physical interface to the virtual asset, it is possible to explore the virtual assets through their physical counterparts.

1.3. Rationale

Within virtual reality worlds, there is a need to create a more complete and cohesive virtual reality experience. Research trends suggest that haptic integration is imperative for continuous presence being maintained by participants in virtual reality spaces (Ramsamy et al, 2006). The sense of presence is often broken or lost when the participant reaches their hand out for a 3D virtual visual object and instead of being able to feel it, they see their simulated hand pass through the virtual asset. Various research interests point towards integrating haptics in virtual worlds to make the experience more convincing. Insko (2001) concludes that “Passive haptics, augmenting a high-fidelity virtual reality environment with low-fidelity physical objects, will markedly improve both sense of presence and spatial knowledge”. In this project, the physical and virtual objects overlap perceptually, creating a continuous sense of integration between the physical and virtual spaces. Oculus Rift researcher Michael Abrash (2016) suggests “The difference in the right combination of stimulus at the right time makes, deeply convincing experiences in virtual reality”.

1.4. Scope and Limitations

This thesis is framed within Human-Computer Interaction (HCI) research and the framework of Tangible User Interfaces (TUI). The tangible interfaces are constructed out of electronic textiles (e-textiles) that promote manual interaction with the hands. These interfaces have been specifically designed to control and manipulate-3D visual assets within virtual reality. This thesis examines the relationship between active manipulation of physical objects/artifacts/interfaces and is viewed through the theory of Active Touch (Gibson 1962, Visell et al. 2016). Further, the theory of Haptic-Visual Overlap has been studied to better understand the relationship between haptic and 3D visual asset associations in virtual reality. The use of virtual reality within this project is limited to using this technology as a screen that renders 3D visual assets and allows digital interaction with these assets. The haptic interactions with objects/artifacts/interfaces that I have developed complement and enhance the 3D visual experience as simulated through a virtual reality headset.

My prototypes are created from e-textiles primarily and composed of DIY textile sensors. These sensors are not standardized and cannot be replicated, and thus are fine-tuned to each interface. In addition, the Framework of Tangible User Interfaces (Ullmer and Ishii, 2000) couples the physical interface to its intangible digital counterpart through the ideas of embodiment and representation. Each e-textile interface has been designed and custom built for their corresponding virtual reality experience.

1.5. Research Questions

1. How might the physical affordances of textiles be used as part of a tangible user interface for a virtual reality experience?
2. How can the conductive and resistive properties of electronic textiles be used to detect different kinds of touch?
3. How can 3D visual assets in virtual reality respond to changing conditions of objects in the physical world?

2. Theoretical background and Framework

This project brings together the framework of Tangible User Interfaces, the theory of Active Touch and the theory of Haptic Visual Overlap into the domain of e-textile interface design and the design of 3D visual asset in virtual reality. By exploring these theoretical frameworks, I developed explorative, electronic, textiles that not only represent and control assets within virtual reality space, but also address and ameliorate the lack of a sense of touch (i.e. haptics) in a virtual reality environment.

The framework for Tangible User Interfaces has allowed me to critically analyze the design process through the framing of a series of intertwined questions that are based on the relationship of the physical e-textile interface with the 3D virtual asset in virtual reality, I also utilized these lenses in my prototype development. These questions primarily address how the e-textile interface controls and represents the embodied characteristics of its digital counterpart. They also relate to the issues of how active touch promotes the use of affordances in the textile material, and how the haptic visual overlap enhances the virtual reality experiences.

2.1 Tangible User Interface (TUI)

HCI researcher Alan Dix (2009) describes his field as “the study of how computer technology influences human work activities.” The term computer technology includes most technology such as PCs, mobile phones, laptops, household appliances, in-car navigation systems and even various other systems that have embedded sensors and actuators. HCI has an associated design discipline referred to as interaction design that is involved with how computer technology can be designed to create ease of use for people. The key aspect of the interaction design discipline is the notion of “usability”, which is often defined as efficiency, effectiveness, and satisfaction. HCI is both an academic discipline studying the way technology impacts human activity and a design discipline aimed at designing technology for maximum usability, effectiveness, and satisfaction (Dix 2009).

For more than forty years people have relied primarily on screen-based text and graphics to interact with computers. In the nineties, there was a movement of incorporating physical objects and artifacts within virtual spaces. One example of this was the early works of Wellner (1993), a final-year PhD candidate at the University of Cambridge Computer Lab who worked as a research scientist at Xerox of EuroPARC on interacting with paper objects on a Digital Desk. Similar trends have been seen in the explorative work of Durrell Bishop, a student at the Royal College of Arts, who designed a prototype telephone answering machine that incorporated everyday objects that were augmented with computation, in order to make digital information graspable (Crampton, 1995).

Ullmer and Ishii (2000) stated that “The last decade has seen a wave of new research into ways to link the physical and digital worlds”, and a similar line of thought has been pursued at the Key Centre of Design Computing and Cognition at the University of Sydney, where researchers are developing tabletop systems that combine Augmented Reality and Tangible Interfaces (Kim and Maher 2008). Furthermore, this approach is reflected in the established practices of the “MIT Tangible Media Group” headed by Hiroshi Ishii through their work on tangible interfaces. The area of Tangible User Interfaces involves physical interaction, virtual environments, and computation as part of the physical world. The word “tangible” is derived from the Latin “tangibilis” and “tangere” which means “to touch.”

2.1.1 Key characteristics of Tangible User Interface (TUI)

Human beings have skills for sensing and manipulating their physical environment, but these skills are not being employed in interaction with the digital world today. The framework of Tangible User Interfaces builds upon these human-based skills and applies HCI approaches that incorporate physical objects and artifacts with computational abilities within virtual spaces. The relationship between the two is that the digital representation embodies the characteristics of the physical representation. The coupling of physical objects/artifacts/interfaces and their 3D virtual counterpart in virtual space allows the participant to use their skill set (i.e. interacting with objects in the physical world) to access virtual objects. Ishii and Ullmer (1997) describe this as the "seamless extension of the physical affordance of the object into the digital domain."

In a comparison between the traditional Graphical User Interface (GUI) model (i.e., computer screen and mouse) and the Tangible User Interface (TUI) model, Ullmer and Ishii (2000) note that the TUI model incorporates the GUI model, but it splits the output of the GUI into Physical Representation (rep-p) and Digital Representation (rep-d). In this model, the digital representation "control and physical representation" (tangible interface) embody or takes on the characteristic of the "digital representation" (rep-d).

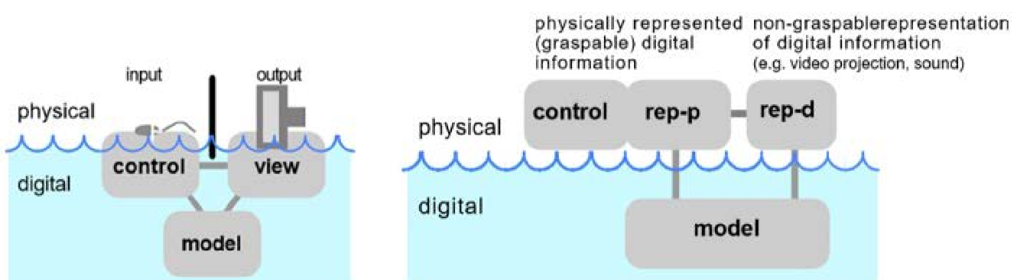

Fig.2 GUI and TUI. Comparison of Graphical User Interfaces (GUI) (left) and Tangible User Interfaces (TUI) (right) interaction models (Ullmer and Ishii 2000).

Three key characteristics of the framework for Tangible User Interfaces, outlined by Ullmer and Ishii (2000), are presented below as direct quotes from their research:

1) "Physical representations (rep-p) are computationally coupled to underlying digital information (model). The central characteristic of tangible interfaces lies in the coupling of physical representations to underlying digital information and computational models."

The first key characteristic discusses the computational model in relationship to the physical representation (rep-p). The model would use a Unity 3D asset simulator or algorithm to create the required simulation real-time. The computational model also considers the x, y, z location, displacement, and manipulation data from the e-textile's sensor output. These two aspects, namely the real-time simulator along with sensor data, are coupled. This has been further discussed with respect to the prototypes in Chapter 6.

2) "Physical representations embody mechanisms for interactive control. The physical representations of the tangible interface also function as interactive physical controls. The physical movement and rotation of these artifacts, their insertion or attachment to each other, and other manipulations of these physical representations serve as tangible interface's primary means for control."

The second key characteristic discusses control mechanism within the system, where it can be said that the physical representation (rep-p) acts as the control for the digital counterparts (rep-d). The e-textiles have sensors in them and the data received from the sensors during interaction is used to manipulate and control 3D visual assets in virtual reality. The prototypes described in Chapter 6. act as controls for their digital counterpart.

3) "Physical representations are perceptually coupled to actively mediate digital representations (rep-d). Tangible interfaces rely upon a balance between physical and digital representations. While embodied physical elements play a central, defining role in the representation and control of tangible interfaces, digital representations - especially, graphics and audio - often present much of the dynamic information processed by the underlying computational system."

The third of the three key characteristics is the quality of the e-textile interface is perpetually coupled to the qualities of the 3D visual asset in virtual reality. The e-textile physical interface is designed to exploit the affordances provided by the textile materials (e.g., stretching, pushing, and deforming the physical interface). The 3D virtual asset responds to the changes made to the e-textile interface. Various prototypes in Chapter 6. illustrate this.

Where the above three characteristics refer directly to their model, a fourth characteristic of tangible interfaces is also significant.

4) “The physical state of interface artifacts partially embodies the digital state of the system.”

Prototypes discussed in Chapter 6. demonstrate the coupling of physical objects/artifacts (i.e. e-textile interface) with 3D virtual visual assets that are fluid-like in character (i.e. water, air and semi-solids). The stretchable, deformable nature of fabrics allows them to represent fluid-like virtual entities. This characteristic will be further described in relation to the prototypes, which are discussed in Chapter 6. Embodied entity refers to a physical or virtual entity, that represents an idea, quality, characteristics or feeling. In the prototype Boomerang (see Chapter 6) the quality of “stiffness” is embodied in the physical object as well as the virtual entities (i.e. 3D virtual object).

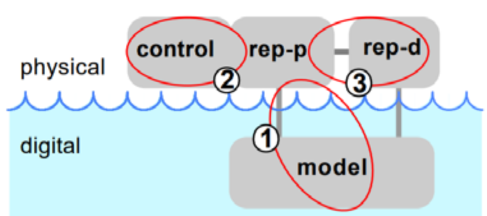

Fig.3 Three key characteristics for ‘Tangible User Interfaces’. Noted above through Ullmer and Ishii paper Emerging frameworks for tangible user interfaces (Ullmer and Ishii 2000).

2.1.2 Distinguishing physical properties of Tangible Artifacts

Tangible user interfaces are systems that use physical artifacts as representations of, and controls for, their intangible digital. The physical artifacts at the center of tangible interfaces, the tangibles/artifacts/objects, have four distinguishing physical properties as outlined in Ullmer and Ishii (2000)

1) Physically embodied "The broadest property and criteria of tangible interfaces is that digital information or functionality is somehow embodied in physical form."
2) Physically representational "The specific physical form of these physical artifacts can vary widely. On the one hand, they can be literally or ironically representational, alternatively, these artifacts can be symbolically representational, bearing no material resemblance to the digital associations for which they stand."
3) Physically manipulability "An important aspect of physical manipulability is that Tangible User Interfaces artifacts are generally graspable." This property has been prominently highlighted by the PhD. Thesis of Fitzmaurice (1996). This means that objects can be taken within the hand, and physically manipulated with the hand and fingers."
4) Spatially reconfigurable "In contrast, the spatial reconfiguration of physical elements - their physical placement and removal, translation and rotation - is the central mode of interaction with tangible interfaces. While these compositional elements often will be mechanically constrained, their spatially reconfigurable state will take on special significance."

The framework of Tangible User Interfaces is well represented through project "Urp" (Fig.4), a TUI made for urban planners and architects where physical building models are used to control digital data visualizations of air flow (represented by the dots), digital shadows, and mirror glare. As the building models are physically shifted by hand, there is a corresponding change in the digital representations. In this system, rep-p is the physical position (x, y), dimensions, and materials of the building, while rep-d is the graphically created shadow, glare, and wind direction. It can be said that the digital representation embodies the characteristics of the physical representation (building models), because the building dimension and position (i.e. real time physical character) directly affect the wind flow in its surrounding area. Therefore, it can be said that the wind flow (i.e. rep-d in real-time) embodies the characteristics of the building (position xy, dimensions real-time). The same can be said for the digital shadows, because when the building models are physically moved and rotated, their corresponding shadows transform accordingly. Hence, the digital shadows embody the character of the physical building model.

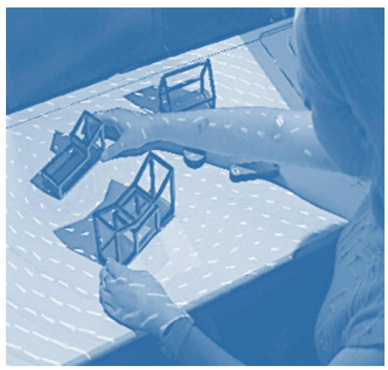

Fig.4 Urban Planning Simulation. "Urp" urban planning simulation, with physical building models and wind tool and probe. (Tangible Media Group, MIT Media Lab 1999)

The computational model for the real-time air flow simulation uses the motion of fluids equation. The computational model also considers the xy locations and dimensions (length and width) of the building. These two aspects, the motion of fluids equation and the building specifications, are coupled, demonstrating the first of the three key characteristics of the framework mentioned above (see Chapter 2.1.1).

This project aims explores a fluid human-computer interaction between a physical fabric interface that acts as both a controller and the digital representation (i.e. rep-d), 3D visual virtual asset, experienced through virtual reality. The various prototypes explored have been designed using the framework of Tangible User

Interfaces and will be discussed in Chapter 6. Ahead, the theory of Active Touch and the theory of Haptic Visual overlap are also discussed.

2.2 Active Touch

In his seminal 1962 paper *Observations on Active Touch*, J. J. Gibson emphasized that being passively touched tends to focus the participant's attention on their subjective bodily sensations, whereas the active exploration of affordances tends to guide the participant's attention to properties of the external environment (Lederman and Klatzky 2009). The term "affordance" (Gibson 1966) refers to actions that are made physically possible by the properties of an object or an environment. Gibson (1962) states that "Active touch refers to what is ordinarily called touching which is different from being touched." This is an important phenomenon when creating passive haptic interfaces for virtual reality since Active touch is "exploratory" instead of "performatory" (Gibson 1962).

Gibson's work is considered a central pillar within the theory of Active Touch. Currently this field is pursued in robotics, where active touch refers to the idea of interpreting touch-instigated signals that are captured by sensors (i.e. sensing mechanism in the robotic skin) whose motion is deliberately controlled to facilitate information gain (i.e. active exploration of object/artifact/interface using robotic hand). Visell et al (2016) state that the term "active" "is applied to the role of motor behavior in eliciting or shaping sensory signals, at least when the movement is intended to capture information via touch."

The e-textile interfaces created during this project are intended to exploit the inherent affordances of textiles (i.e. stretching, pushing, and deforming). These affordances are further accentuated when the interfaces are designed in a way that encourages Active Touch. This has been done by incorporating elements like pleats and folds in draped fabric (see Chapter 6, Concept 1 - E-textile screen partition) or spring-like stretchable and deformable elements using knitted fabrics (see Chapter 6, Prototype 2- E-textile knitted disk interface).

Prototype 3. uses "perceived affordances" (Norman 1998) or the actual properties of the physical object, which determine just how the thing could possibly be used. It also uses the linearity of fabric that takes the form of a fan and allows the fabric to be creased, folded, and opened with ease (see Chapter 6, Prototype 3. E-textile hand fan). Further, 3D shapes that enable fabric deformation by physically squeezing the material (see Chapter 6, Prototype 5. E-textile ball interface) have also been explored. The prototype explorations discussed in Chapter 6. demonstrate how various textile materials have been approached with the idea of promoting affordances and the tactile sense.

2.3 Haptic Visual Overlap

Haptic and visual modalities overlap because they are both sensory systems capable of processing the geometric structure of an object. My research uses the term haptic to describe a form of nonverbal communication (Hans, 2015) that incorporates the sense of touch. Through vision and touch, complex three-dimensional (3D) geometric properties of objects can be recognized. Vision is the modality we most often use to identify objects, but the tactile system (or haptics) is also useful, particularly in situations where objects cannot be seen. This directly affects the control of 3D assets within virtual reality environments as discussed below.

In 2001, Newell reported that the visual system recognizes the front view of the object and the hand recognizes the back view of the object. He stated, "hands recognize the objects best from the back" (Heller et al. 2002). In his PhD thesis, Fitzmaurice (1998) stated that the overlap of "haptic-visio" space is what completes 3D perception of a physical object for a human being in physical space. The incorporation of physical objects into virtual environments facilitates grasping behaviors and innate spatial reasoning skills for object manipulation (Fitzmaurice 1995, 1998).

Haptics can also provide information about the weight, compliance, and temperature of an object as well as information about surface features. This kind of information is not readily available by looking at the object. Vision can provide information about color and surface patterns, and both haptics and vision can give information on the volumetric shape. The haptic system can only operate within arm's reach but when objects are in range they can be manipulated and thereby reveal the structures and features of unseen surfaces and parts, thus satisfying both visual and haptic system. (James, Keith Humphrey, Gati, Servos, Menon, and Goodale 2002)

Haptic modality encompasses various haptic cues from the physical interface that are triggered at the time of tangible interaction. These cues are the feel of 3D shape (volumetric shape), compliance (i.e. material stiffness or flexibility), thermal quality, weight, and surface texture. Likewise, the visual modality encompasses various visual cues from the physical or 3D virtual interface, and these cues include 3D shape (volumetric shape), color, and pattern.

A. 3D Volumetric Perception and Depth Perception

The overlap of "haptic - visual" modalities improve the 3D volumetric perception of a virtual object in virtual reality because complex, 3D, geometric properties can be recognized when vision is combined with touch. It has been noted that haptic sensations (i.e. force feedback) are known to impart users with realistic feeling about physical interactions and these sensations improve the control over virtual objects in a 3D simulated space as noted by Bouguila, Ishii, and Sato (2001) in their paper concerning the testing of grasping 3D objects in Stereoscopic spaces.

Depth perception is one of the critical issues in virtual reality (Naceri, Chellali, Dionnet, and Toma, 2010). In "Depth Perception of Virtual Environments", Bouguila, Ishii, and Sato (2001) suggest that participants rely on the apparent size of the 3D asset when making depth comparisons in virtual reality. Uncontrolled feedback cues in a 3D virtual environment can provide false depth information, which can create a sensory conflict leading to distorted visual perceptions and unskillful interactions. Artificial display systems (i.e. virtual reality headsets) and feedback cues (i.e. active or passive haptics) have to work in concert with each other to create the illusion of a sense of interaction. In the real world, human senses such as vision, audition, haptic, etc. are almost always in agreement with each other, and thus accurate depth perception is usually possible (Bouguila, Ishii, Sato, 2001).

As demonstrated in a study by Cooper et al (2018), the integration of haptic and visual perception leads to faster, responsive, performance than when the haptic or visual cues are perceived in isolation. In their experiment, the task was to change the wheel on a virtual racing car in a 3D environment as fast as possible using a 3D haptic device (i.e. active and passive haptics together). Their results showed that the combined input of tactile and visual sensory cues led to a reduced mean completion time compared to when only haptic cues were available on their own.

B. Compliance (force)

Compliance is the scientific term used to describe the stiffness or flexibility of a physical material. It also refers to the resistance of a material to deformation. When a participant is asked to interface with and manipulate a material, visual priors come into play because experiences of force occur in the context of visual experience. It has been suggested that the sensation of force through mechanical interaction with materials, and the corresponding displacements perceived by vision, become associated with long-term memory. Klatzky and Wu (2014) state, “Kinematic features in a visual percept can be matched to stored haptic experiences to infer force.” This idea has been used in Prototype 2 (see Chapter 6, Prototype 2. E-textile knit disk interface) and Prototype 5 (see Chapter 6, Prototype 5. E-textile ball interface). In those prototypes, the displacement of e-textile materials results in corresponding changes to and displacements of the 3D visual assets. For a satisfactory interaction with physical materials their flexibility and/or tactile feel should correspond to the visual distortion in the volumetric shape of the material. In an experiment to deduce or discriminate spring stiffness, a number of participants were exposed to a physical spring apparatus and screen based visual feedback. This experiment noted that the minimum difference in intensity required for discrimination increased for the “haptic feedback only” condition, while in the case of “haptic + visual feedback” condition it was reduced (Klatzky and Wu, 2014). Haptic Visual overlap, 3D volumetric perception and material compliance within various prototypes are discussed in Chapter 6. These prototypes demonstrate how different textile materials have been approached with the idea of promoting “Haptic-Visio” overlap.

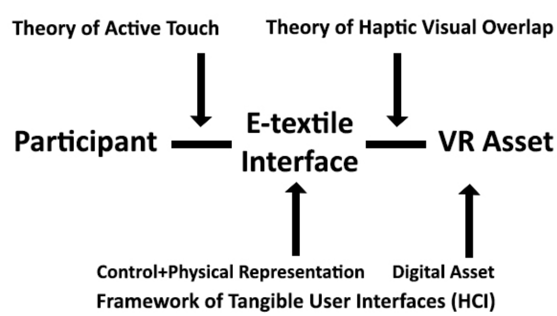

Fig.5 Theoretical Framework for this research

In conclusion, it can be said that the framework of Tangible User Interfaces, when applied to the design of e-textile interfaces and 3D virtual visual assets, leads to an explorative space where the physical and digital intuitively overlap to create an enhanced experience. The information within virtual reality can only be accessed through the graspable, interfaces, where the material affordances of these interfaces guide the participant during the interaction. The questions that arise from the coupling of the tangible user interface and the 3D virtual assets are primarily how the e-textile interface controls, represents, and embodies characteristics of its virtual counterpart. The theory of Active Touch is poised in the interaction space created primarily for human hand action and the e-textile interface, where it promotes the use of affordances in the textile material. Thus, it can be said that the intuitive exploration of the e-textile is a way to explore the 3D visual asset in virtual reality. Further, the theory of Haptic-Visual Overlap is positioned in a space between the e-textile interfaces and virtual reality as seen in Figure 5. The compliance (i.e. stiffness or flexibility) of physical materials and their 3D virtual representation enhances the virtual reality experience. A contextual review of works that explore interfaces through tangibles and promote active touch and haptic-visual overlap, is discussed later.

3. Contextual Review

This chapter reviews e-textile research projects that contribute to the area of Tangible User Interfaces and explore the theory of Active Touch and Haptic-Visual overlap. The features of Tangible User Interfaces include physical objects and artifacts that act as representations and controllers for their digital counterparts. Within the projects mentioned here are objects/artifacts/interfaces that can be exploited for their physical and tactile affordances, as these affordances are meant to guide the participant during interaction (Ullmer and Ishii, 2000), as described in detail in Chapter 2. Research in the field of textile-based interfaces supports haptics (i.e. sense of touch Chapter 3.5) as a means of introducing a more innate and intuitive interaction with computer technology. These ideas are built around creating expressive interactions, as it can be said that the tactile input of data into the system is not cerebral but intuitive. "Intuitiveness" is defined as human understanding that allows for operation without explicit instruction. Our repeated exposure to materials and interactions with them evokes such an intuitive understanding of them. Because we are surrounded by textile materials in our everyday environment, there is research to make fabrics computationally intelligent, including in the physical-digital interaction space.

In the early nineties, work emerging from the Xerox Research Lab diverged from traditional Graphical User Interfaces (GUI) models that utilized a mouse, keyboard, and monitor as an input, towards the model of Tangible Interfaces that involved input devices or controls that utilized physical object/artifacts. These physical object/artifacts were enabled with computational ability through sensor-based technology, and their inclusion within digital spaces imparted specific meaning to the digital context. In the late nineties, academic work related to tangible interfaces using e-textiles emerged from MIT Media Lab. This is seen in the example of the e-embroidery wearable music jacket (Post et al, 2000), which consists of an embroidered conductive thread keypad connected to a wearable MIDI synthesizer and speaker circuit. The evolution of haptics within digital spaces as proposed by Fitzmaurice et al (1998) involved touching and interacting with an object. He stated that this kind of interaction helped cognition and used examples of early calculating devices like the Abacus, which requires physical interaction with beads. He further stated that digital data would be better understood when attached to physical objects within the digital space. In 1992, Shimoga et al, reported that haptics help cognition and improve user response.

Moving on from haptics that help in the cognitive understanding of data within digital systems towards haptics that evoke intuitive responses in users, this research addresses the latter. Margret Orth researches the confluence of tangible interfaces and e-textiles. She worked on academic projects with tangible interfaces for manipulation and exploration of digital information (Gorbet, Orth, and Ishii, 1998). She further developed her interest by creating tangible computing interfaces and computational devices from electronic fabrics and conducting threads (Orth, Post, Cooper 1998). One of Orth's project is the Embroidered Musical Ball interface, which is composed of sewn conductive electrodes acting as pressure sensors for modulating sound (Orth 2000).

In early 2000, Do-it-yourself (DIY) toolkits enabled the DIY community to experiment with e-textiles and wearable computers by using familiar materials and techniques (e.g., textiles and sewing). New electronic textile material and integration techniques have led to growth in DIY e-textile sensor movement (Buechley, 2006) this further promoted ways of constructing material based haptic interfaces.

An Interactive wall (2010) designed by the High Low tech group (MIT Media Lab) encouraged users to run their hand across a wallpaper constructed out of paper, paint, and Arduino sensors. The wallpaper was attached to a paper computing kit that allowed users to turn on a lamp, play music, or send a message to a friend.

The application of this ideology (i.e. haptic inclusion) can be seen in more recent commercial projects that aim to make e-textiles more broadly available to the public. Companies like Eeonyx (Eeonyx 2018, https://eeonyx.com/) and Google's Jacquard project lay the foundation for making e-textiles readily available for incorporation into digital lifestyle products. These products have the potential to be introduced into digital spaces where different modalities can meet. Haptic have been studied as a part of e-textile affordances for the last two decades as a means of communication within digital technology. In recent years, some studies proposed various haptic inclusion devices (i.e. force feedback). However, this research focuses specifically on passive haptic objects/artifacts for virtual reality 3D visual asset manipulation.

The projects mentioned in the following section provided the foundation for my work in e-textile research and have influenced the design of the objects/artifacts/interfaces mentioned in Chapter 6. With this overall view in mind, while looking at design trends and technological development in e-textile interfaces, several projects by various groups are covered next chapter.

3.1. Tangible Textiles as Interfaces

Tangible interfaces often exploit the way humans use their hands to interact with objects. The research projects detailed below are limited to interactions that, specifically and only, incorporate hands and fingers. Tangible interfaces using fingers include *swipe* or *pinch*, whereas tangible interfaces that are built around hands point towards interactions such as *grasping* or *grabbing*, but can also include interactions that are finger-specific.

A. 'Touch' 'Swipe' or 'Drag' Interfaces

Fig.6 Cilllia-3D printing Functional Hair.

3D Printed Hair acting as a touch sensor (Ou, Ishii MIT Media Lab 2016)

In a research project by Ou and Ishii (2016) that encourages touch and swipe interactions named Cilllia, which is focused on 3D printing Functional Hair at the MIT Media Lab's Tangible Media Group, describes a method for 3D printing hair-like structures on both flat and curved surfaces. Their project involved building a software platform that would allow users to create their own 3D printed hair geometries. This system can print minute hair geometries that are smaller than 50-100 microns. Hair grows in a directional order and follows a certain pattern specific to a certain area of the body, thus allowing for touch sensing in human beings. In this study, Ou and Ishii (2016) state that "The ability to fabricate customized hair-like structures enables us to design passive actuators and swipe sensors. We also present several applications that show how the 3D-printed hair can be used for designing everyday interactive objects." This project enables and promotes a 3D printing systems that can create touch-based sensors from microfibers. When these microfibers are attached to electronics, they create tangible artifacts. When a user interacts with these artifacts through touch or dragging their finger across their surface, they create data specific to the interaction, which is a primary requirement of Tangible User Interfaces. This project demonstrates how tactile cues enhance spatial understanding of objects (Fitzmaurice 1996). It can be seen how the deformable quality of the fibrous material is being explored through the finger, where the user can use the fibrous texture to judge the directional change in the order of the fibers, hence guiding their interaction further via these cues.

Fig.7 Tangible Textural Interfaces, Eunhee Jo, Royal College of Art graduate (2012)

Royal College of Art graduate Eunhee Jo (2012) designed a tactile music speaker with a fabric control panel and a speaker that responds to music. The control panel for the Tangible Textural Interface (TTI) speaker is embedded in a concave surface on one side. By pushing the knit fabric surface forward, backwards, up and down, the user can skip tracks, adjust the volume, or access various options on the equalizer. The stretch fabric acts as a passive haptic response to the user. On the other side, the speaker's surface pulsates to the beat of the music and physically responds to selections made on the control panel. This non-screen based design effectively demonstrates the use of passive haptics. The knit fabric accommodates the deformation of material as the user interacts with the surface of the control area. While in the speaker area, the physical shape changes and the textile material responds to the music. The speaker embodies a certain character of music as it pulsates to the beat as the participant controls the music (Jo, 2012).

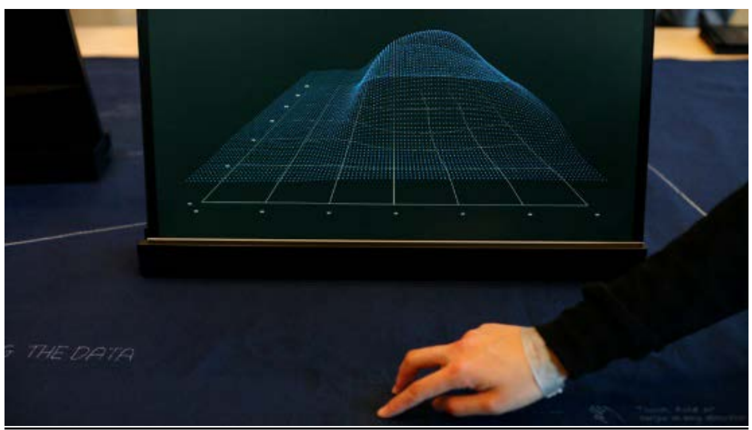

Fig.8 User interacting with touch sensitive denim, Google's Project Jacquard (Poupyrev 2016)

Project Jacquard (Poupyrev, 2016) is a recent initiative by Google. The project researches various conductive yarns that are amendable to being woven using the current textile manufacturing technology. The woven fabric that incorporates the e-yarn can be used for various purposes and is currently being marketed by Levi's in a denim jacket (i.e., Commuter jacket). The general idea of this project is to "deploy invisible, ubiquitous interactivity at scale" (Poupyrev 2016). The resulting e-textile can be used to manufacture soft toys, furniture, apparel and bags, automotive or home interiors, and many other everyday lifestyle products. Any object made using Google's Jacquard textiles can be digitally interactive and computationally responsive (Fig. 8). These kind of technological development points towards a trend that will create the foundation for more tangible, material, inclusivity in digitally interactive spaces. This has been expressed directly as Poupyrev (2016) states that "Consequently, for designers of these objects, digital sensing and computation will become basic properties of the textile materials- like weight, color and elasticity."

B. 'Grab' 'Squeeze' and 'Stretch' Interfaces

Fig.9 The Fabric Keyboard (Wicaksono and Paradiso, MIT Media Lab 2017)

Fabric Keyboard (Wicaksono and Paradiso, 2017) is a deformable, textile, music keyboard, based on a multimodal, fabric, sensate surface. Each key on this keyboard can detect touch, proximity, pressure, stretch, and coupled electric fields simultaneously, resulting in rich discrete and continuous gesture sensing as well as touch sensing. This enables unique tactile experiences and new interactions both with gestures such as pressing, pulling, stretching, and twisting of the keys or fabric, as well as non-contact by hovering and waving towards/against the keyboard's electromagnetic source. The dual abilities of contact and non-contact gesture-based control allow the performers to be more expressive. According to Wicaksono and

Paradiso (2017) "This enhances the relationship between the physical interaction and the music, as the fabric deeply embodies the sound it resonates."

Fig.10 Chang and Ishii demonstrating interaction with fabric as a part of ZStretch
(MIT Media Lab 2007)

In their project, Z-Stretch, Chang and Ishii (2007) describe a textile music controller that supports expressive haptic interactions like stretching, deforming, pulling, and pressing. Chang and Ishii describe various ways in which ordinary hand interactions can be supported by fabrics (Fig.10) and how they can be used to control music. The musical controller takes advantage of the fabrics' deformational constraints to enable proportional control of musical parameters such as frequency and pitch. Chang and Ishii (2007) claim, "This novel interface explores ways in which one might treat music as a sheet of cloth." Their project is based on the idea that stretching fabric can provide rich and dynamic expression and input to the creation of music. Fabric can allow for a wide range of interactions, and the idea of stretching is closely linked with musical manipulation. In sound editing software, one can often "stretch" a piece of music by increasing the duration or pitch. In the physical world, the deformation of materials is often coupled to sound, as when wooden beams creak as they bend or when a string is bent by plucking it. Through their research, Chang and Ishii have demonstrated a way of connecting fabric materiality and the haptic qualities of the interface. In general, the Zstretch fabric controller supported regular fabric interactions like stretching, grabbing, and twisting on both the regular planes and edges. Stretching any part of the edges allowed the different sound parameters to be changed. Users would typically use a combination of one-handed and two-handed movements during interaction.

Fig.11 Felt Sensors (2015), Lara Grant, Interactive Telecommunications Program, NYU

In a study by designer Lara Grant, various felt-based interfaces were created by embedding e-textile sensors inside felted shapes to explore pressure and stretch sensing. Her felted 'Stretch sensor' neck wrap and 'Pinch and Location' interfaces use grab and pinch interactions that add to a more exploratory haptic vocabulary. This enables unique tactile experiences and new interactions (Grant, 2015).

In conclusion, it can be said that tangible textile interfaces often exploit the affordances created by the deformable nature of fabric. Such deformations can include, but are not limited to, stretching, pulling, pressing, folding, and dragging the objects/artifacts/interface. These e-textile interfaces are equipped with computational abilities and are able to sense the way humans interact with them. When a user interacts with these artifacts through touch or dragging their finger across the surface, a certain kind of data is captured that is specific to the interaction, and this is a primary requirement of Tangible User Interfaces. The specificity of the data is further reflected in the digital or virtual space that these interactions represent. Like in the case of the Commuter jacket (i.e., the Google Jacquard and Levi collaboration), as the user taps the touch sensitive denim fabric data received from tapping is converted into a specific action that can be applied to controlling a mobile device. The same can be observed in Eunhee Jo's knit fabric speaker interface (Fig.8), where by deforming the fabric control panel the user can access various selection options. Thus, each interaction has a specific outcome. Various projects have demonstrated a way of connecting fabric materiality and the haptic qualities of the interface to data.

Furthermore, these projects also demonstrate how tactile cues enhance the spatial understanding of objects (Fitzmaurice 1998). This is greatly reflected in the project Fabric Keyboard (Wicaksono and Paradiso, 2017) where researchers relate the physical interaction with fabric to the music in a way that suggests the fabric embodies the music. The same line of thought is reflected in Zstretch's proposed fabric music controller where the researcher has attempted to map the deformation of the fabric caused during interaction to various sound frequency (Chang and Ishii 2007). Thus it can be said that embodiment, control, and representation are central themes. Chapter 3.3 covers recent projects that specifically use e-textile interface in virtual reality.

3.3. E-textile and Soft Interfaces for Virtual Reality

Chapter 3.3 summarizes projects that use e-textiles and alternative, soft, interfaces within virtual reality spaces. One notable project is Stella Speziali's thesis and virtual reality research called, "Tangible Worlds" (Speziali, 2017). Her project offers a sensory, virtual reality experience where the user interfaces with the virtual reality world through touch. The tactile experience is fundamental in this experience, since the virtual reality space is visually controlled through fabric. As the user interfaces with the fabric, the abstract visual patterns within the virtual reality experience change. The sensors within the fabric are commercially available flex sensors and the microcontroller is an Arduino UNO. This project establishes a strong link between reality and virtual reality through touch. Speziali (2017) says, "What we perceive from the outside, does not represent what we live inside the virtual world. This project reflects on how to manipulate the reality and influence the virtual world and vice versa. I'm trying to explore what is means to touch some strange materials without seeing our hands and see something happening in the virtual world."

In another project, researchers at York University introduced diegetic, tangible, objects in virtual reality narratives (Harley, Tarun, Germinario, and Mazalek, 2017). Their system is made of commercially available hardware and a sensor unit designed to track a physical object represented within the virtual reality space.

The same sensor setup has been used with various custom made objects as well as other tangible objects like a cube, a stuffed animal, a treasure chest, and a wooden boat. This project is particularly exciting for two reasons. It addresses narrative in virtual reality spaces and also questions the relevance of traditional button type controllers. Harley et al state, “While controller-based interactions are the current standard in consumer virtual reality, their tangible and tactile qualities communicate limited information about the objects they represent or the story world in which they exist.” This stands in contrast to another approach, where everyday objects are introduced to virtual reality to direct gameplay. The gyroscope tracks the orientation of the object within the virtual reality space and each tangible object has a specific meaning and interaction designed for it. The researchers have attempted to demonstrate through this project “passive and active haptics” to bridge the gap between the real and the virtual worlds. They include physical characteristics of the physical objects represented in the virtual space to expand the possibility of interaction. In the case of the stuffed squirrel, a 3D digital representation was created to be used within virtual reality. In their project, both active and passive haptics were utilized. Active haptics were utilized for programmed digital feedback and used time vibrations during interactions while passive haptics provided feedback about the weight and texture of an object.

Harley et al (2017) emphasize the use of passive and active haptics for tangible objects and state that “Bringing these considerations together expands the design space of tangible narratives, first in the choice of the objects themselves, and second in the visual affordances of virtual reality, as any object can gain or lose its visual attributes.”

In contrast to traditional handheld controllers, various soft, fabric, glove based controllers were introduced in the CES 2017. One example is the Noitom Hi5 VR gloves developed by Richard Borris. These gloves offer hand and finger tracking for the HTC Vive VR headset. The device claims to have full-hand motion capture and sensors that interact with 3D objects in virtual reality spaces. They also claim to have an orientation output rate of 90 frames per second, which is the industry standard for quality virtual reality today. These gloves ensure hand and finger tracking by orienting the hand and allowing each finger to bend independently. Flex sensors and a gyroscope, positioned within the glove, send motion and hand position data via Bluetooth. The hardware calculates the average bend of the finger, ten finger joints, and the overall orientation of the hand. During the installation, the user inputs their finger length by engaging in a short calibration. The HTC Vive position sensors are strapped on the wrist. The rest of the data is extrapolated to find the location of the shoulder and arm after which the data is then used to model the wrist and arm real-time. These types of virtual reality glove controllers are developed by independent hardware peripheral developers in collaboration with companies like HTC Vive and other virtual reality gear makers. They are then introduced to game developers and the virtual reality development community who are encouraged to build games and environments around these controllers.

Fig.12 Noitom Hi5 VR gloves 2017

Noitom Hi5 VR gloves 2017 (Left), 3D model hand representation in VR as tracked using the Noitom Hi5 glove 2017 (Right)

These gloves are extremely good at recreating the hand and finger movements and orientation in virtual space. The manipulation of 3D virtual asset is customized for glove type interactions and haptic cues based on force feedback mechanism guide the interactions with the 3D virtual assets.

In conclusion, recent projects in virtual reality that include unconventional interfaces, and use tangible e-textiles, are successful at creating sense-based input to virtual reality (Speziali 2017). There is an overall movement and trend that points towards creating an intuitive interaction (Harley, Tarun, Germinario and Mazalek 2017) where artifacts, materials, and techniques are being created to develop interfaces that move away from being merely input devices (i.e. handheld controllers for virtual reality) and towards experiential interfaces (Speziali 2017). The haptic experience is fundamental in these interactions because these projects offer a sensory, virtual reality, experience where the user interfaces with the virtual reality world through tangible objects

In the following section, I review how commercial controllers manipulate 3D assets within virtual reality.

3.4. 3D Asset Manipulation using Current Controllers in Virtual Reality

This section covers various virtual reality controllers and interfaces that are mainstream, as well as research into traditional 3D asset manipulation and how that differs from the interfaces built as a part of this project. 3D manipulation tasks include selection (acquiring or identifying an object or subset of an object), positioning (changing the objects 3D position), rotation (changing the objects 3D orientation), and scaling (uniformly changing the size of an object) (Poupyrev et al, 1997).

Mainstream controllers (Fig. 14) are defined as interface or controller (hardware) that are constant and support many virtual reality games (software) that are built around these existing controllers. Mainstream controllers are generic, so that they can be adopted by a general population. Their design is based upon the shape, position of fingers, and ergonomics of human hands.

When using mainstream controllers, the interaction within virtual reality spaces occurs through a virtual interface. The controller assists the user to choose from virtual interfaces and relies on UI signifiers. On these controllers, when a user pushes a button they see their hands move or they manipulate specific items. The user must quickly understand interaction concepts without an expert to explain the interface. The HTC Vive and Oculus Rift controllers have no finger tracking, but they are designed so that users intuitively understand the button's function by the button's physical touch, placement, and position.

Fig.13 UI signifiers/labels in the hands in mainstream VR controllers

Mainstream controllers differ from the interfaces that have been created during this project because while the commercial controllers control virtual assets and successfully manipulate 3D virtual assets, they neither represent nor embody the characteristics of the 3D assets. This is a distinguishing factor for Tangible User Interfaces, the interface represents or embodies characteristics of the 3D virtual asset as well as controlling it. In a Tangible User Interface, the affordances guide the interaction as the passive haptic builds on intuitive real-time responses from the participant while they handle the e-textile interface with one or both hands. The real-time change in the e-textile interface is computationally mapped to the 3D virtual asset. In the case of a glove-based methods used to imitate realistic interactions with 3D virtual objects, the virtual hand is made to change shape on contact or trigger force feedback or sound feedback. One such method is described by Alvas, Marchal, and Lecuyer (2012) in their paper, “The God-Finger Method for improving 3D Interaction with Virtual Objects through Simulation of Contact Area”. They believe the glove-based method allows more realistic manipulation of 3D virtual assets because the participant relies on interaction between their hand and the asset, whereas, in the case of commercial controllers, the user is taught affordances through signifiers and force feedback. In tangible user interfaces the affordances are through active touching (Gibson, 1962), while the glove provides/offers passive touching through force feedback. Here the term “3D Asset Manipulation” means spatial rigid object manipulation in a virtual reality environment.

Fig.14 Commercial Hand Held VR controllers.

Oculus Gear VR Controller (Left), HTC Vive Controller (Center), Oculus Rift Controller (Right)

Fig.15 The Climb VR Game (2017) for Oculus Rift + Touch Controllers.

This Climb VR game is sold specifically for Oculus Rift and in Fig. 15, it can be seen that the Rift controller takes the shape of hands in virtual reality and the grabbing action is only possible through pressing down on buttons on the controller. The 3D virtual object manipulation techniques used by these are grasping and pointing.

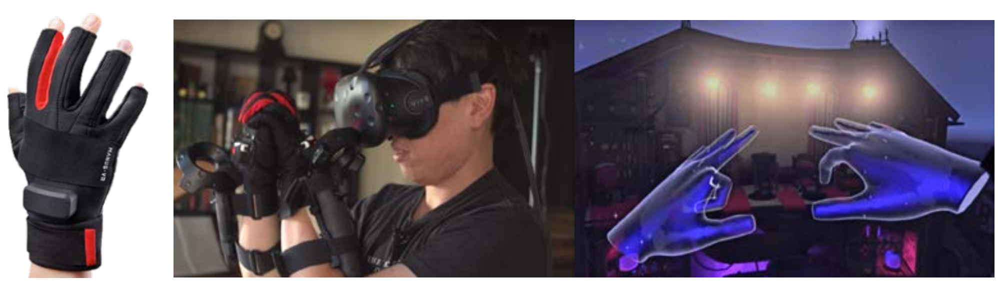

Fig.16 Manus VR Glove (2016).

(Middle) Glove and handheld controllers strapped to the arm. This provides the position sensor data.

Specifications of the Manus VR glove (Fig.16 and 17) include full finger tracking, haptic feedback, gyroscope, accelerometer, and magnetometer to measure orientation. The glove is completely wireless, powered by cells, and has a latency of 5ms. The Manus VR Glove calculates the relative position of the hand. To get positional tracking of the gloves, it relies on the tracking solution of other systems, such as Xsens and Vive Tracking. Any tracking solution that gives the location of the wrist can be used to provide positional tracking.

Fig.17 Manus VR glove in live interaction with assets in VR

While these gloves are extremely good at recreating the hand-finger movement and orientation within the xyz space in 3D, their interaction between the 3D virtual asset and the 3D hand model is extremely limited. However, in most virtual reality systems, when these two modalities are coupled together, the real world users and the virtual world are separated and do not interact directly with each other.

When the participant is asked to grasp a 3D virtual object, thus understanding the task of grasping, a graphic hand usually emerges in the 3D virtual scene while the participant uses their real hand to control the interaction. In this kind of interaction, the participant feels that the 3D graspable object is at a remote site, thus associating the interaction with an “indirect control” and disassociating with the virtual environment itself, it keeps the real and the virtual worlds non-fused. They remain two separate and distinct environments. This effect of disassociation is primarily due to the lack of depth perception within 3D virtual environments (Bouguila, Ishii, and Sato, 2001) and also the lack of the haptic experience of the 3D virtual asset. Through this discussion we have established the differences in approaches to 3D asset manipulation in virtual reality using mainstream controllers vs. the interfaces that have been created as part of this project to augment the sensate qualities of the virtual reality space using the haptic visual overlap (Fitzmaurice 1998) and Active Touch (Gibson 1962).

3.5. Haptics

Haptics is a form of nonverbal communication (Hans 2015) that incorporates the sense of touch. The term “haptic” which contains the Greek root meaning “to fasten” suggests the interactive nature of the sensations. Part of the body is “fastened” to a part of the world, and feedback results from the active exploration of a surface object by the limbs, hands, and skin of the user (Biocca and Levy, 1995).

The sense of touch is one of the five major senses (Hans 2015) and is considered a continuous sense. In other words, we are always using our sense of touch, consciously or unconsciously, even when we are sleeping. In his study on the history of the senses, Robert Jutte (2005) noted that the human race has entered a “haptic age”. McLuhan in 1964 said that the new age of electronic media would be defined not by vision but by “touch”, as electronic media emulated the tactile sense in their capacity to universally translate data for the different sense modalities (Parisi, Paterson, and Archer, 2017).

Within the context of virtual reality, “haptic” refers to the science of applying tactile sensations to human computer interaction (HCI). The advent of this kind of technology in mainstream HCI is mainly to do with touch screen mobile phones where incorporating “haptic feedback” (vibration) to screen based interfaces offers an extra dimension to interacting with these electronic devices. The feedback sensation was introduced to compensate for the lack of physical keypad on the purely screen based phone. So the vibration function of the phone is used to simulate the tactile feel of buttons (Jang, Kim, Tanner, Ishii, and Follmer, 2016). The extension of this mainstream phenomenon, is seen within virtual reality or 3D environments because it is considered an important aspect for feeling truly immersed within these environments. The most common haptic feedback is vibration, or electrostatic shock produced by external devices, such as specially developed gloves, shoes or joysticks, that are in contact with the user's skin. These forms of haptic feedback are usually triggered while the user is trying to interact with certain 3D visual assets within the virtual reality environment (Michael Abrash, Oculus Summit 2016). In the same line of thought Shimoga (1993) suggests that, "Haptic imagery could greatly enhance our exploration and use of the virtual worlds, a number of studies show that haptic feedback can reduce the time it takes to complete manual tasks as much as 10%-75%." If all information, even abstract information, could be physically touched and manipulated, our ease of understanding and our sense of presence can be significantly increased (Biocca and Levy, 1995). This research is significant for creating tangible interfaces for virtual reality.

Within the scope of this paper, "haptics" refers to the resultant phenomenon that takes place while the user is made to physically interface with various textures and material objects using their hands. In this context, the "haptic feedback" generated is self-created in a sense that the user is generating feedback for themselves while interacting with the physical interface, so there is no externally or artificially induced haptic feedback through vibration or electrostatic shock.

4. Material Review: Electronic Textiles

Electronic Textiles (e-textiles) are textile materials, fabrics, yarns, and threads that have incorporate conductive fibers and other elements during their material construction (i.e. weaving, printing, embroidery). My research is concerned with creating soft electronic sensors using e-textiles that control 3D virtual visual assets in virtual reality.

This contextual review covers the physical aspects of e-textiles, their materials, creation and manufacturing techniques as well as offering examples of research projects and construction done within the past fifteen years. E-textile materials can be categorized as sensors, actuators, energy sources, and circuit creators (Castano and Flatau, 2014). I have specifically used sensors and circuit creators as e-textile materials. I have developed several e-textiles sensors and incorporated them with various textile materials as discussed in Chapter 5. Sensors can be made from e-textile materials and provide sensing properties of different nature including capacitive, resistive, optical, and solar. I have developed various DIY resistive textile sensors for my interfaces (see Chapter 1) using conductive thread, conductive wool, and conductive paint (see Chapter 7). I used conductive yarns and metallic wires to create circuits and connections between sensors and the microcontrollers to build my prototypes.

4.1 Conductive Threads and Yarns

Fig.18 Conductive thread and yarns

E-textiles use conductive yarns (Fig.18), these provide the various interconnectors between the circuit elements. The yarns can be made of metal thread wrapped around a non-conductive core or onto fine fibers where a metal core has been covered by a non-conducting yarn. Most conductive fibers are made from intrinsically conductive materials such as steel. Galvanization is known to increase yarn conductivity by two or three orders of magnitude (Bleckley, Eisenberg, Catchen, and Crockett, 2008). Conductive threads and yarns are made by either spinning or twisting continuous conductive material with non-conductive material. The most commonly used conductive yarns are spun from strands of silver or stainless steel. This allows even non-conductive materials to turn into conductive yarns. These yarns and fibers can then be made into fabrics using various construction methods like, weaving, knitting, felting etc. A common characteristic of conductive yarns is that they are silver grey in color with a shimmery silky look. The resistance of these yarns can be lowered by twisting multiple strands of the yarn together. Conductive yarn textile manufacturers and suppliers worth mentioning are Bekaert (2018), LessEMF8 (2018), and Lamé Lifesaver (2018), which are all located in North America. Lamé Lifesaver is a company in British Columbia that sells small spools of conductive silver coated nylon thread that can be used for transmitting low amounts of electrical current through a textile. The thread has a resistance of 88.5 Ohms/m and is particularly and can be used in the bobbin of a sewing machine (Berzowska and Bromley, 2007). For this thesis, I sourced stainless steel conductive thread of 0.2mm thickness and 2 ply from Spark Fun Electronics that had a standard resistance of 28 Ohm/ft, and stainless steel conductive yarn with a thickness of 0.4mm, 3 ply thread, 1.0 Ohm/inch.

4.2 Conductive Wool

Fig.19 Conductive wool from Eeonyx

This conductive wool has been made by applying Eeonyx's conductive polymer StaTex to synthetic, staple fibers. These fibers can be further spun into yarns and blended into fabrics but for this project they have been used in a number of ways to create pressure sensors (see Chapter 6). They have a resistance value of 200-500ohms/sq.

4.3 Conductive Paint

Conductive paint (Fig. 20) is electrically conductive, nontoxic, and water-soluble. Conductive paint can be applied to various surfaces using a paintbrush or by using printing processes like screen-printing. To be able achieve consistent electrical performance, the paint should be applied in an even layer. Using conductive paint is a fast and easy way of creating textile circuitry and can easily be made using a textile printing screen (43T screen recommended for Bare Conductive Paint). After drying, the paint is somewhat flexible, but this flexibility depends on layer thickness and choice of substrate. These paints are intended for use with low voltage DC power sources at low currents and have not been tested with sources exceeding 12VDC. Higher voltages are not recommended (Bare Conductive, 2018).

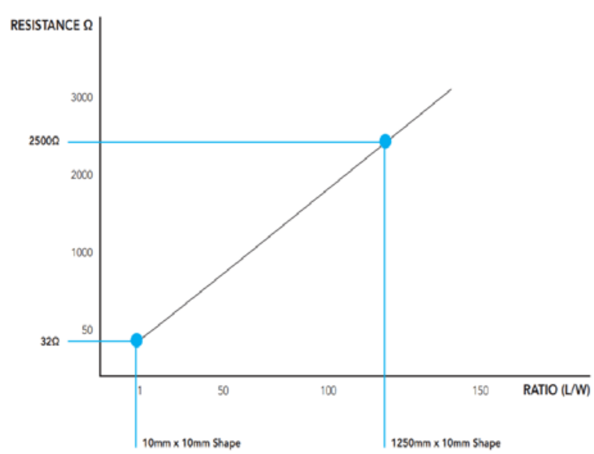

Fig.20 Bare Conductive Electric Paint.

The diagram plots the proportional ratio of a sample of electric paint against its approximate resistance.

4.4 Attachment of Hardware Components to Textiles

Buechley and Eisenberg's (2009) paper on fabric PCBs, electronic sequins, and socket buttons is concerned with one of the most challenging aspects of creating e-textile prototypes, something they describe as the issue of "engineering the attachment of traditional hardware components to textiles". They present three techniques for attaching off-the-shelf electrical hardware to e-textiles. The first method is where the design is made of fabric PCB or iron-on circuits that can be ironed directly to textiles. I used this technique in the creating a DIY fabric flex sensor that used pressure resistive fabric enclosed between two fabrics with ironed on conductive strips. In the second method they describe the use of electronic sequins as a way to create wearable displays and connect other electronic artifacts that make up the circuit through them. In the third method they describe the use of socket buttons to facilitate connecting pluggable devices to textiles (Buechley and Eisenberg, 2009).

Influenced by those methods, I developed techniques for attaching e-textile components to fabric substrates and the components formed a design on the fabric's surface. By stitching thread fibers in patterns, electronic elements can be made out of conductive thread, possibly with multiple crossings, in order to achieve the desired electrical properties. I also developed passive elements formed with conductive paints that were developed using painting techniques applied to fabric substrates. I also built resistive elements by adjusting the dimensions of an already coated conductive polymer knit fabric and created conductive knits from scratch by incorporating conductive yarn in the knitting process as discussed in Chapter 5. A noteworthy resource for any e-textile novice or professional is a public website titled *How To Get What You Want*, where in order to share their ongoing work in e-textiles, Perner-Wilson and Satomi (2009) gather documentation and present information in an organized way. The website is organized in categories that include example projects, solutions such as circuits, connections, sensors, materials, tools and techniques.

4.5 Electronic Textiles

This section of the contextual review covers a brief history of e-textiles and their applications in projects over the past 15 years. These projects are prototyped using materials briefly discussed above. E-textiles can be made into clothing and other interior objects such as bedding, curtains, rugs as well as other fabric based artifacts. Researchers in the field of e-textiles are creating soft interfaces instead of hard electronic devices that are prevalent in the market today.

Post and Orth (2000) developed both simple and sophisticated e-textile engineering methods that used embroidery of conductive yarns to act as data and power busses, resistors, and capacitors on fabric, which lead to the development of capacitive sensing cloth touch pads and the use of gripper snaps in e-textile applications.

In early 2002, Jayaraman, a researcher at Georgia tech, began a project in e-textiles titled, "Georgia Tech Wearable Motherboard. The project was funded by the US Department of Navy. In this research, a vest-like garment is woven out of optical fibers and conductive yarns that have been integrated with other electronics. The garment can detect bullet wounds and monitor physiological signs like heart rate and temperature. This data can be downloaded and analyzed by doctors and researchers to get an indication of the wearer's physiological patterns.

Perner-Wilson and Buechley (2011) describe various textile sensors constructed from a selection of electrically conductive fabrics, threads and yarns using sewing needles, pompom makers, crochet hooks and spool knitting machines in their paper *A Kit-of-No-Parts*. This research concentrates on DIY e-textile sensors and their application on a fabric tilt sensor. The tilt sensor is a free-swinging metal bead strung on a piece of conductive thread surrounded by six petal shaped pieces of conductive fabric. Depending on the direction of inclination, the metal bead will make electrical contact with different petals that enable the differentiation of six different positions of tilt. By replacing the discrete conductive petals with a resistive track this sensor becomes a crochet potentiometer (Wilson and Buechley, 2011).

Another project to the intersection of traditional craft and smart materials is Butterfly Lace, a project by Kuusk, Kooroshina, and Mikkonen (2015). Butterfly Lace is lace that behaves as both a conductive multi-color sensor-actuator structure and is made from conductive yarn and thermochromic ink. To control the color change on the yarn by human touch, the yarn is set up as part of an electric circuit, which uses the yarn itself as a sensor. The duration of the touch is measured by using a capacitive sensor and the heating power is set according to the measured duration. Brief touch is needed for a small trigger and maximum power is achieved after a few seconds of touch. This can be adjusted to different yarns and required feedback as necessary.

In project FlexTiles, Parzer and Vogl (2016) created a flexible, stretchable, pressure-sensitive, tactile input sensor consisting of three layers of fabric. They demonstrated in this project how FlexTiles can cover large areas, 3D objects, and underlying, deformable shapes. The sensing material consists of two layers of zebra fabric with one layer of piezoresistive EeonTexTM LG-SLPA in-between. The two layers of fabric are orthogonally oriented and form a matrix layout. These projects demonstrate how e-textile sensors can be constructed out of existing materials by assembling them in a specific ways.

In the projects mentioned above, different e-textile construction techniques have been reviewed through available literature. Some e-textiles are constructed from scratch using techniques like crochet and knitting (i.e., DIY e-textiles), in others conductive yarn is introduced as a part of the structure (Wilson and Buechley, 2011) while others are constructed using the assembly of various kinds of commercial e-textile sensors (Parzer and Vogl, 2016). For the purposes of this thesis project both of these methods have been used to create responsive textiles sensors as detailed in Chapter 6.

5. Methodology

Research through Design (Frayling 1993; Sanders 2008) is a well-known research methodology. It involves researching, conceptualizing, creating, and testing in an iterative manner. This project explores the Framework of Tangible User Interfaces and theories of Active Touch and Haptic Visual overlap. During the first half of the thesis, the work involved reading and studying these theories and their influence on interfaces, haptics, and visual perception. At the same time, I conceptualized ideas that would incorporate these theories into my practice of design of e-textile interfaces and its 3D virtual counterpart in virtual reality.

During the creation process the first step is materials research. Various commercially available e-textile raw materials were purchased (i.e. conductive yarn, wool and paint) along with non-conductive textile materials (i.e. nylon, polyester fabrics, yarns and filaments). Several sensors were developed using a combination of conductive and non-conductive materials, and further, these sensors were applied to textile explorations that work towards the construction of the physical objects/artifacts/interfaces. Also, various e-textile fabric constructions were explored to understand the qualities of the material that would accentuate the affordances of textiles as described in prototype Chapter 6 (i.e. draped pleated screen, flexible knit disks, and deformable ball).

The development work was specific and customized to each concept and prototype as discussed in Chapter 6. The data captured by the sensors was translated to the manipulation of 3D visual assets within the virtual reality space.

Certain amount of work was undertaken while building the 3D visual assets in virtual reality that involved creating mesh deformation in primitives in the Unity 3D virtual reality platform as well as creating assets in Blender with rigging and importing them into the Unity 3D virtual reality platform. The e-textile interface and the virtual reality asset are coupled together through the framework of tangible user interfaces, thus, changes in the physical interface resulted in changes made to the 3D visual asset.

Three dynamics that appear during a Research through Design project during the development phase are: coupling, interweaving, and decoupling (Basballe and Halskov 2012). During the initial step of coupling, research and design interests are united and the basic frame and constraints of the project serve both levels of interests. During the coupling phase the constraints set by the theoretical framework define design decisions. This can be seen in the constraints set by Tangible User Interfaces concerning tangible artifacts. The framework defines tangible artifacts as having properties such as being physically embodied, physically representational, physically manipulable, and spatially reconfigurable. These points guided the design constraints and in turn influenced the design of e-textile object/artifact/interface.

During interweaving, research interests and design interests influence each other as processes, methods, and validation are established. The process of interweaving can be expressed through the creation of a series of prototypes. The research work undertaken through the theory of Tangible User Interface, Active Touch and Haptic Visual overlap, helped me understand and define the parameters under which explorative e-textile interface could be designed to control 3D assets within virtual reality.

When considering the e-textile squishy ball interface (see Chapter 6.5, Prototype 5) the framework of Tangible User Interface suggests the physical objects/artifacts/interfaces to be physically embodied, representational, and manipulable. This is literally reflected in the 3D virtual, visual, counterpart of Prototype 5 (see Chapter 6.5, Prototype 5). The squishy ball interface accommodates the theory of Active Touch through the affordances provided by the e-textile materials. The soft, deformable form and the flexible materials guide the user towards exploring affordance of the interface indicating, that the use of multifold layered soft fabric textures would be desirable and would further enhance interaction. These ideas were tested using iterative design and testing of physical objects/interfaces. Haptic Visual overlap suggests that 3D mapping of physical interface with the virtual object should be such that visual deformation of 3D virtual assets should be distinctly identifiable.

Decoupling appears at later points of the project when the designer/researcher focus on one of the interest set (design or research). This happened for me during the time of creating the design artifact/object/interface. At this point the design inputs were being consolidated through the making process. In the making or creating or the production phase of the physical artifact/object focuses on the design process, but is also appeared during the final evaluation and inquiry when the research interests become the focus of the work.

This practice-led research utilizes my skills as a textile designer and my understanding of textile-based materials and also merges with my interest in developing e-textile interfaces for virtual reality.

6. Prototypes and Process

This section covers the conceptualizing and creation of my prototypes. It also unpacks how I've applied theoretical frameworks to each of these objects/artifacts/interfaces designs.

6.1 Concept Development 1. Fluid Screen Partitions

6.1.1 Concept Description

Concept 1 is a tangible e-textile interface to an existing 3D interactive water system built with the Unity 3D virtual reality platform. This iteration is only at the concept stage, but it is important because it illustrates my ideal physical situation to exhibit this design; a textile screen made of multiple layers of soft polyester. This light, movable, fabric creates a partition that provides both a division of space and concealment.

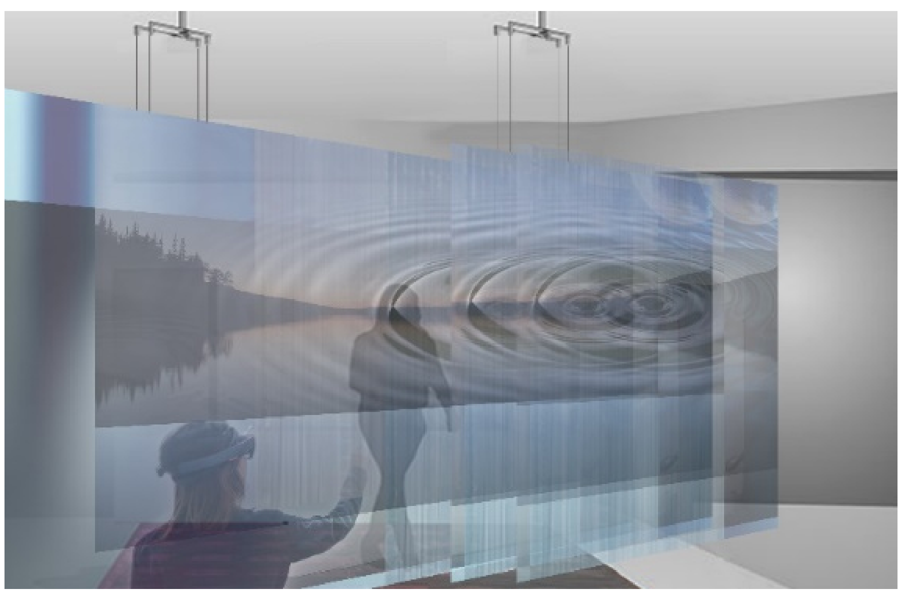

Fig.21 Artistic visualization, of the virtual reality environment and the e-textile screens.

These act as a tangible interface between the real and virtual world depicted in the virtual environment. This fabric is made in plan weave, providing no stretch. When draped, it falls straight into many fine pleats. This has been illustrated in Fig. 21. where I wanted to create a visual and thematic parallel between the fabric, its texture, and the 3D visual asset in virtual reality. (Fig. 22a & 22b).

The folds of fine fabrics have characteristics similar to the gentle rippling patterns that can be observed in water, this prototype embodies the physical representation of water, and symbolically discuss the theoretical framework of Tangible User Interfaces (see Chapter 2.3.2).

The tangible interface described was proposed to be created from soft multilayered screens made of sheer fabrics, these would hang like partitions within a room space. While interfacing with these, with touch or slight sweeping gestures (Fig.21) these would translate into interactions within a 3D virtual water system. Here the intangible representation is a 3D virtual asset that is a fluid (i.e.water).

A sweeping hand, gesturing across the fabric, would causes the fabric to gather and distort, and because of this, there is a change in resistance in the e-textile. This change in resistance would be captured as data and is used to control a 3D water asset in the virtual reality environment. Points located within the 3D water system would be mapped to the x,y points within the e-textile. The data captured by the sweeping hand against the e-textile would be plotted against the frequency of wave pattern in the 3D interactive water system, causing an increase in ripples.

Similarly, the hand gesture and the action of pushing the e-textile away from the body would cause the parallel layers of e-textile to interact with each other, changing the resistance in the e-textile. Data captured during this action would be plotted against the axis that controls the height of the wave pattern in the 3D interactive water asset. Hence, giving meaning to individual hand gestures, as they relate to respective changes in the 3D interactive water system within Unity platform. The sensors used to create this prototype would be a combination of flex sensor (on individual screens) and resistive yarn (between screens).

Concept 1. suggests that “computation” and “interface” are both required to move into the physical environment. This means that, the interface is not in the virtual space but in the physical space and also that the interface has computational abilities that allows the participant to connect with the virtual environment, allowing them to control the 3D visual asset. The interactions described here rely less on logic (i.e. pressing buttons on a controller) and more on intuition (i.e. like interfacing with drapes or curtains).

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Fig.22a Concept 1.

Interactive tangible e-textile screens

Control + Physical Representation (Control+ rep-p)

Fig.22b

Intangible representation (VR asset)

Digital Representation (rep-d)

Qimono, 2007, (Pixabay)

Fig.23 Suggested gestures for Concept 1.

Gestures and its interpretation as visualized in VR and applied to a 3D water asset.

Partyzan, 2009, (Wikimedia Commons)

6.1.2 Application of Framework

Tangible Interfaces are both representation and controls for their intangible representation (Ullmer and Ishii 2000) and physical e-textile screens are used to control digital data of water ripples (represented by the concentric lines), depth and shadows. As the e-textile screens are physically shifted by hand, there is a corresponding change in the digital representation of water ripples, depth, and shadows. In this system physical representation (rep-p) is the physical position of parallel screens between each other (xyz), and displacement of fabric form original location during interaction, while the digital representation (rep-d) is the graphically created shadow, graphically created depth and graphical ripple direction. It can also be said that the digital representation embodies the characteristic of the physical representation (e-textile screens).

Let's look at this in detail. The position of screens in relation to each other (xyz) and the displacement of fabric during interaction (its physical character real-time) directly affect the water ripples in certain areas of the 3D water system. Therefore, the water ripple (real-time) embodies the characteristics of the e-textiles (screen position xyz from each other, and displacement of fabrics real-time). This is also true for the digitally created shadows, as the e-textile screens are physically moved by hand, the digital shadows transform accordingly. Hence, the digital shadows embody the character of the physical e-textile. The computational model for Concept 1. uses a Unity 3D water asset from the Unity store that would create the water ripple simulation real-time. The computational model also considers the xyz location between screens and displacement of the screen fabrics, and these two aspects, namely the water ripple simulator along with e-textiles displacement specifications, are coupled together demonstrating one of the three key characteristics of the framework relating to coupling of the computational model and the physical representation mentioned in Sectiosn 2.1.1.

Discussion TUI

I could question the physical elements (fabric screen placement in physical space) ability to spatially reconfigure as discussed in Chapter 2.3.4. I could also question how the physical textural qualities (folds and drape) of the fabric screens could be altered to represent multiple characteristics of the 3D virtual water asset, particularly the frequency of water ripples (represented by the concentric lines), and depth and shadows. In this prototype the material quality of the soft fabric screens has been connected to water to enhance the virtual experience of water within the virtual reality space. The affordances were created through the drape fabric form and the pleated texture.

Discussion Active Touch

Concept 1. describes a soft, fabric, multilayered, screen partitions in a room that acts an exploratory interface to a virtual reality experience. The softness of the fabric allows for an “exploration” based interaction.

Discussion on Haptic Visual overlap

Concept 1. was developed in tandem with Prototype 2. Prototype 2 was an instinctual answer to making a more hand centric object/artifact/interface that allows the user to manage and manipulate the interaction using their hand. This prototype also relates to a fluid Unity 3D asset that behaves like water only it is now a hand-based object. Prototype 2. is illustrated in Fig. 27.a and Fig 27.b ahead.

6.2 Prototype 2. Knitted Disks

6.2.1 Prototype Description

Prototype Idea 2. (Fig.24) describes an interface that has multiple, flexible, disk shapes linked together using a stretch knit fabric that acts an interface to a 3D water asset in virtual reality. The knit fabric allows the interface to be stretchable and tangible, where the flexibility of the disk allows displacement and manipulation in the interface. Through the action of pushing, pulling (displacement of fabric) the participant interacts with the e-textile interfaces. The user's manipulation causes the resistances in the e-textile to change and this change in resistance is captured as data that is used to control a 3D water system in the virtual reality. The sensors used to create this prototype were a combination of pressure sensitive fabric (disks) and stretch sensitive knit fabric (outer casing).

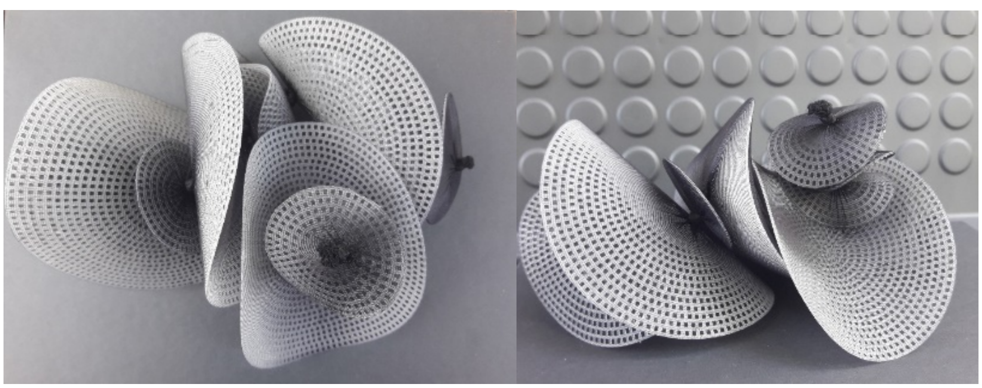

Fig.24 Tangible e-textile interface made from resistive knit fabric and flexible insert.

As the user interacts with the interface (Fig.25, 26) the resistance within the fabric changes. The change in resistance is recorded as data and is transferred to an asset in Unity 3D virtual reality platform using a Bluetooth module. Points xyz located within the 3D water system is mapped to the xy points within the e-textile and displacement (z point).

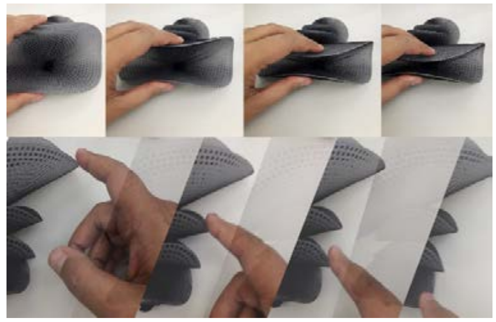

Fig.25 Image demonstrating the flexibility of the interface.

Fig.26 Image demonstrating stretch qualities in the interface.

This prototype mainly deals with capturing changing resistance within the e-textile. The manipulation of 3D assets within virtual reality is directly proportional to the quality of data acquired during the user transacting with the interface. When the user interacts with the interface, the interface should be sensitive enough to capture finer aspects of the physical change made to it by the user. The data acquired by the finer aspects of the user's actions on the interface and it resultant effect of it on the 3D virtual asset in virtual reality, display the control the user has over the virtual asset. The quality of control of the virtual asset results in accentuation of virtual sensation. The data captured during the action of pinching or squeezing of the e-textile would be plotted against the frequency of wave pattern in the 3D interactive water system, causing an increase in ripples.

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Fig. 27a Prototype 2.

Interactive tangible e-textile discs

Control +Physical Representation (Control+ rep-p)

Fig. 27b

Intangible representation (VR Asset)

Digital Representation (rep-d)

Freedesignfile, 2018, (All Free Vector)
Used under Creative Commons License

Fig.28 Suggested gestures for Prototype 2

Gestures and its interpretation as visualized in VR applied to a 3D water asset.

Petras Gagilas, 2009, (Flickr Commons)
Used under Creative Commons License

While the data captured during this action of pressing of fingers against the stretched knit fabric in the interface would be plotted against the axis that controls the height of the wave pattern in the 3D interactive water asset. Hence, giving meaning to individual hand gestures, as they relate to respective changes in the 3D interactive water system within Unity platform. In this prototype exploration, the 3D virtual water asset was created using pre-existing shaders in Unity 3D (Fig. 29). The 3D virtual water asset was very abstract and it was modelled from 3D concentric discs to which pre-existing unity shaders were applied and these could be controlled with the e-textile interfaces seen in Fig.29, Fig.30 and Fig 31.

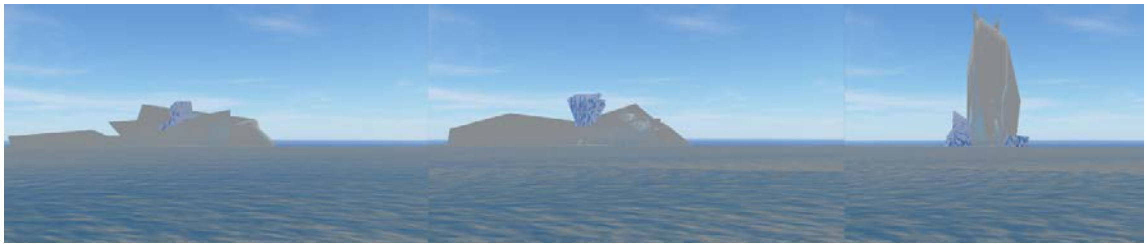

Fig.29 Water Asset in Unity 3D created from 3D concentric disks and pre-existing water shader.

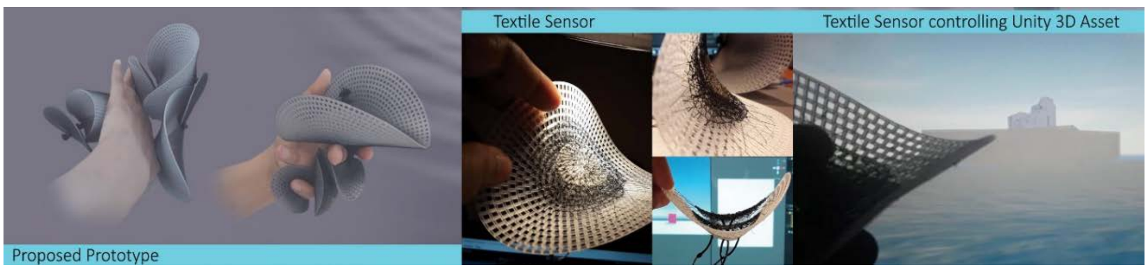

Fig.30 The image above describes initial working aspects of Prototype 2 with crochet flex sensor.

The e-textile interface was created using conductive yarns that were made into a pressure sensor. The data acquired from the sensor was applied to the movement of the virtual 3D disk assets. Tapping the surface of the interface would result in movement within the virtual water asset causing the 3D virtual disc elements within it to rise and fall.

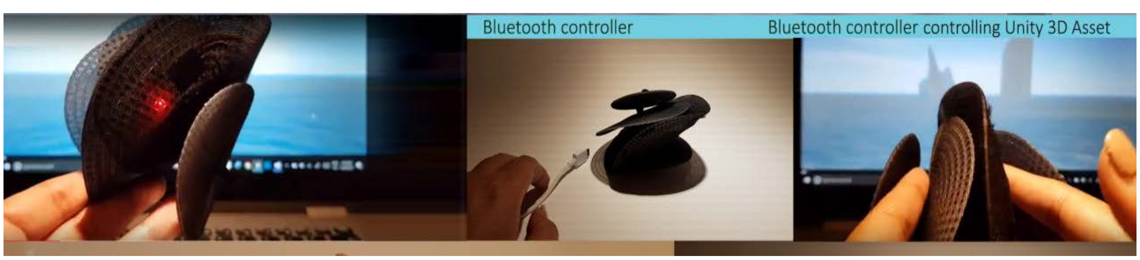

Fig.31 The image above describes initial working aspects of Prototype 2 with light sensor.

In this prototype exploration (Fig.31), the 3D visual virtual water asset was created using Unity 3D shaders. It was modelled from concentric discs elements and could be controlled with the e-textile Bluetooth controller.

6.2.2 Application of Framework

This physical e-textile disk interface represents and controls a 3D water asset in Virtual Reality. As the e-textile disks are physically shifted, manipulated, and spatially reoriented by hand, there is a corresponding change in the digital representation of volume, form, and texture of the 3D water asset within the Virtual Reality space. The suggested interaction and the effect of it on the 3D asset is described in Fig.32. In this system, physical representation (rep-p) is the e-textile disk interface, while the digital representation (rep-d) is the graphical created volume, form, textures in the 3D water asset. The digital rep embodies the characteristic of the physical rep (e-textile disks) but the representation is symbolic, not literal.

Fig.32 Suggested interaction with e-textile interface and associated effect on 3D water asset in VR.

Unknown Lens, 2017, (Pxhere)
Used under Creative Commons License

The e-textile, physical position of disks from each other (xyz), and displacement of disks during interaction (its physical character real-time) directly affects the water form as suggested in Fig 32.2. Therefore, it can be said that the water ‘form’ and ‘volume’ (real-time) embodies the characteristics of the e-textiles (disk position xyz from each other, and displacement of fabrics real-time). The same can be said for spatial orientation of the interface, as suggested in Fig.32.1. As the e-textile disk is physically rotated, the digital water transforms accordingly and mimics flowing water. The computational model for Prototype 2. would use a Unity 3D water asset from the unity store. This asset would create the water form simulation in real-time. The computational model considers the xyz location between disks and displacement of the disks that creates the sensor data, these two aspects, namely the water simulation and e-textile disk interface physical affordances are coupled together, demonstrating one of the three key characteristics of the framework as mentioned in Chapter 2.1.1.

Discussion TUI

Prototype 2. attempts to give dimension, volume, and movement to water and builds on its 3D fluid quality, demonstrating its ability to form 3D shapes (Fig.32). From this I developed a *Grasp and Hold* e-textile interface (Fig 27a). Some of the key characteristics of the framework that informed my decision are discussed below.

A. The knitted disk interface (i.e. Physical representations (rep-p)) is coupled to underlying computational model that accounts for 3D water simulation in Unity 3D virtual reality platform as well as sensor data from the knitted disk interface that registers change in the shape or orientation of the interface.

B. The knitted disk interface (i.e. Physical representations (rep-p)) embodies mechanisms for interactive control of the 3D virtual water asset. By changing the physical form or orientation of the e-textile knitted disk interface, it is possible to change the form of the 3D virtual water asset. This has been illustrated in Fig. 32 through a series of possible suggested interactions.

C. The knitted disk interface is perceptually coupled to the 3D virtual water asset or digital representations (rep-d), these can never been seen apart within the system of the Tangible User Interface.

D. The stretchable, deformable nature of fabrics (i.e. behavior) allow them to represent fluid, like 3D virtual entities. This ability of fabrics to be molded, deformed, and shaped during interaction enable them to embody characteristics of water.

Distinguishing physical properties of Tangible Artifacts with respect to Prototype 2. is discussed below.

A. Physically embodied: The shape and form of water as illustrated in Fig. 32. is embodied within the shape and form of the physical artifact/interface. The change in the shape and form of the disks during interaction result in corresponding change of the 3D virtual water asset.

B. Physically representational: The representation here is symbolic where an interface made of multiple flexible disk shapes linked together using a stretch knit fabric represents a 3D water asset in virtual reality.

C. Physically manipulable: These artifacts are made of soft meshes and stretch knit fabric that allow deformation and extension as illustrated in Fig. 32.

D. Spatially reconfigurable: These artifacts can be spatially reconfigurable in 3D physical space and can be rotated and moved freely as illustrated in Fig. 27a.

Discussion Active Touch

Prototype 2, an e-textile interface made of a series of disks bound together using a knit fabric, leverages the tactile response from a knit fabric that has been stretched over a 3D surface. This prototype can also be spatially manipulated, squeezed, and deformed (Fig 25, 26, 32) allowing for various affordances of the interface to be used. Active touch can also be described as “tactile scanning” (Gibson 1962, Visell et al. 2016). Inspired by the current developments of textile sensors and the stretchable nature of knitted fabrics, I attempt to address these issues and needs by designing haptic sensation intended at amplifying the haptic visual overlap in virtual reality through the use of organic forms (i.e. disk shapes) that could overlap and depict water.

Discussion Haptic Visual Overlap

Haptic visual overlap has been demonstrated through Fig 32. Interaction with e-textile interface results in corresponding change in the visual form of the 3D virtual water asset in virtual reality. The nuances here lie in the coupling of the interaction and the associated change in the 3D water asset. As seen in Fig. 32.3 that tapping gesture would result in creation of splashes while tilting the interface as seen in Fig. 32.1 would result in free flow.

6.2.3 Prototyping

Gesture 'Tap'

I started exploring some of the general gestures that are associated with tangible interaction. 'Tap' is illustrated in Fig 37.3. This e-textile exploration was done specifically for creating computational surfaces for a knitted disk interface as discussed in Prototype 2. In this prototype, two layers of conductive fabric have been stretched across a deformable and soft plastic. As the top surface of the fabric is tapped, it hits the bottom surface, and this creates a change in the value of the data. Depending on the intensity of the tap, the data received from the sensor changes. This data from the sensor is used to manipulate a 3D water asset in Unity 3D.

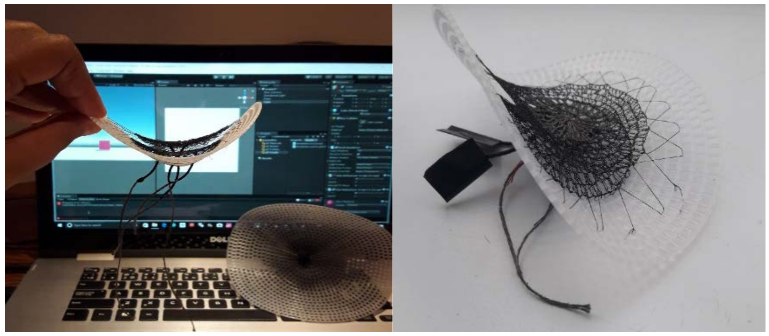

Fig.33 In the image above shows a flex/pressure sensor in crochet.

In this exploration, the fabric has been crocheted out of conductive steel and single ply yarn. The fabric was further stretched on to the plastic mesh using single filament nylon thread. This made the construction feel bouncy and provided an engaging haptic experience. This bounce was further reflected in the movement of the 3D water surface. Two layers of conductive fabric can be seen, these interact to create a flex/pressure sensor, where a flex/ pressure sensor output range can be acquired during user interaction. The image above shows the sensor in use and Unity 3D assets are controlled through the 'Tap' gesture.

6.3 Prototype 3. Crochet Switches and Conductive Ink Resistors

Gesture 'Drag'

In a second exploration with the same materials as described above (i.e. nylon monofilament and single ply steel yarn), various disk-shaped floral crochet switches were created, as shown in Fig 40. The extreme peripheries of the switch and the central portion of the switch are made out of conductive steel single ply yarn. When contact is made between the edges or periphery of the switch and the center, the circuit is complete. This happens when the flexible nylon edge of the disk-shape is turned over towards the center with the finger as shown in Fig.34.

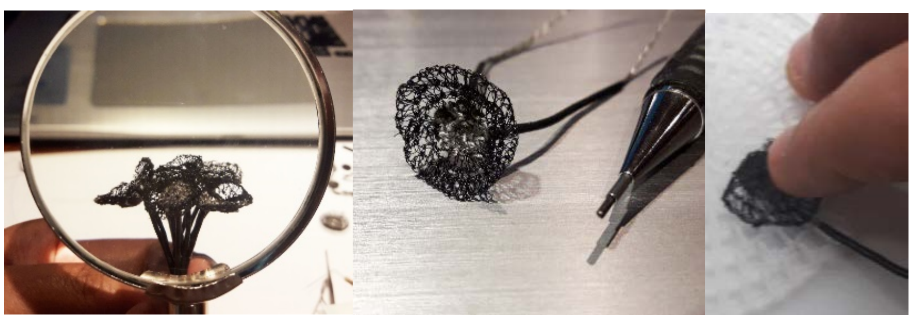

Fig.34 The image above shows a number of e-textile crochet switches that are held together.

These switches can be used as digital inputs to control 3D visual assets. When these switches are arranged on a flat surface, the act of dragging a finger across the surface triggers them. A combination of fiber and electronic textile materials can be used to create an e-textile interface that can input data to control 3D virtual visual assets. In another exploration of "drag", a series of resistors were created using conductive paint.

I created a series of explorations using conductive paints (Fig.35) that were layered on to a fine knit fabric. The amount of applied conductive paint applied determined the resistance of the material. As the layers of paint-increase the conductivity of the material increases. By controlling the layering of conductive paint, it is possible to tune the resistance value of the textile substrate. These resistors were created on stretchable fabric and can be stretched and applied to the surface of various objects rendering them with electronic properties that can be made computational when attached to a microcontroller and power source. The only disadvantage to these materials and techniques is after conductive paint dry they have a tendency of cracking and flaking.

Fig.35 Study showing resistivity range with conducive ink.

The **left** image shows a study of creating a resistivity range with conductive ink that can be applied to fabric surfaces. The **middle** image is conductive paint applied on nylon fabric. The **right** image shows a series of explorations using conductive painted layers to create a series of resistances.

6.4 Prototype 4. Hand Fan Interface

6.4.1 Prototype Description

Prototype 4. describes a physical handheld fan controlling a virtual air/wind generator that is acting on a fabric asset in Unity 3D virtual reality.

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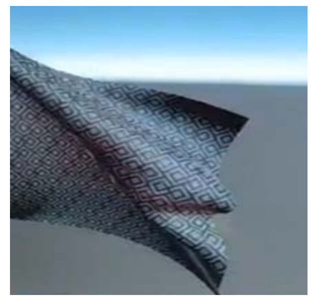

Fig.36a Prototype 4.

Interactive tangible e-textile handheld fan

Control +Physical Representation (Control+ rep-p)

Fig.36b

Intangible representation (VR asset)

Digital Representation (rep-d)

In this prototype, the intangible representation is air, which is visually represented through the flight of the fabric within the virtual reality. The virtual fabric asset 'OBI Fabric' was purchased from the Unity Store in 2018.

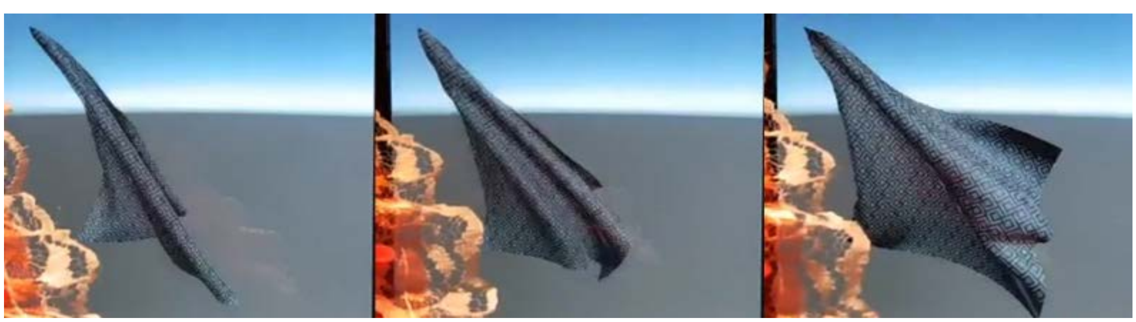

Fig.37 E-textile interface and 3D fabric asset interaction.
The act of fanning in the physical space leads to correspondence change in the wind condition within the virtual reality space. This is visually reflected by the change is fabric flying in the wind.

When compared to the screen-based experience, the virtual reality experience accentuates the feel of the interaction. It does this by blocking out other visual, peripheral distractions and centers awareness on the movement of the fabric and the feel of air as it bounces off the surface of the skin as the fan moves. The visual difference is also experienced by being present in the space with the 3D asset, as opposed to viewing it remotely though a screen.

The 3D virtual fabric asset is rendered in 3D visual space (i.e. virtual reality headset) vs. a 3D virtual asset being rendered in 2D visual space (i.e. flat screen), this causes the interactions with 3D assets within 3D spaces to be visceral and intuitive instead of cerebral.

6.4.2 Application of Framework

This physical e-textile hand fan interface represents and controls a virtual air/wind generator, the effect of the wind is directly reflected in movement of a 3D fabric asset in virtual reality. As the e-textile fan is opened and closed, and reoriented in physical space, there is a corresponding change in the digital representation of 'form' of the 3D fabric asset within the virtual reality space. The suggested interaction and the effect of it on the 3D asset is described in Fig.37.

In this system the physical representation (rep-p) is an e-textile hand fan interface, while the digital representation (rep-d) is a wind generator represented through the graphical created 'movement' in the 3D fabric asset. The digital rep embodies the characteristic of the physical rep (e-textile fan) and the representation is literal, where air movement is physical space is being reflected in air generator within the virtual space.

In another visualization the e-textile fan interface represents and controls a virtual light within a concept 3D room as described in Fig 38. As the e-textile fan is physically manipulated there is a corresponding change in the digital representation of 'light and shadow' within the concept 3D room space. The digital rep embodies the characteristic of the physical rep (e-textile fan) and the representation is symbolic. The e-textile fan interface incorporates flex sensor and gyroscope to track movement and orientation.

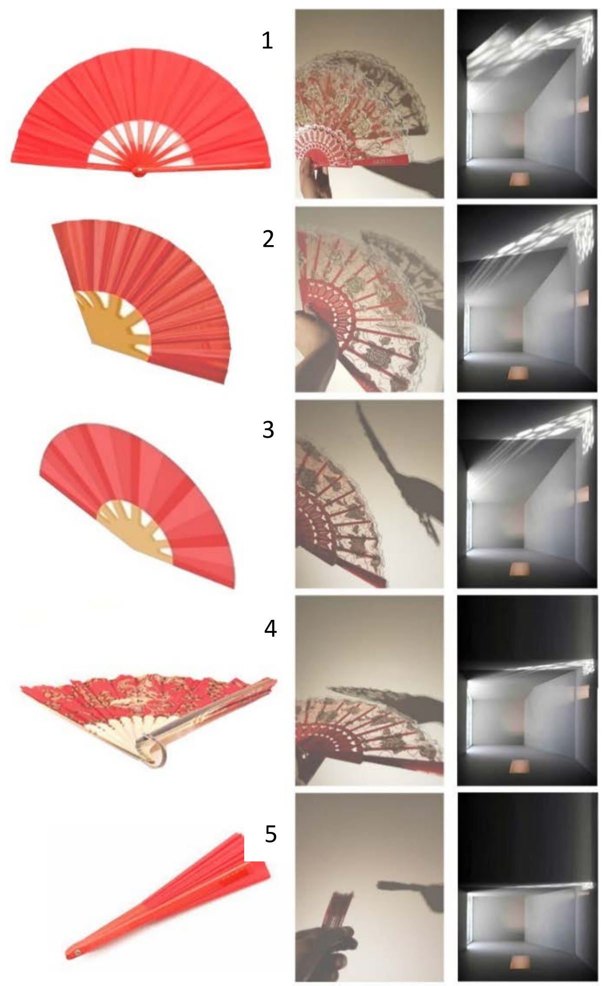

Fig.38 Spatial Configuration of the e-textile fan interface. Spatial Configuration of the e-textile fan interface in physical space and its corresponding effect in light and shadows. In a concept virtual reality room space (extreme right).

Chinese Fan, 2017, (Pxhere)

Discussion TUI

Prototype 4. describes a physical hand fan controlling a virtual air/wind generator that is acting on a 3D fabric asset in Unity 3D virtual reality. This prototype explores the material qualities of linearity of textiles and their ability to be folded. I developed an e-textile hand fan interface (Fig 36a). Some of the key characteristics of the framework that informed my decision with respect to Prototype 4. are discussed below:

A. The e-textile hand-fan interface (i.e. Physical representations (rep-p)) is computationally coupled to an underlying computational model that takes into account the 3D wind simulator in Unity 3D virtual reality platform, as well as sensor data from the hand-fan interface as it registers a change is movement, when the fan is open and in use.

B. The e-textile hand-fan interface (i.e. Physical representations (rep-p)) embodies mechanisms for interactive control of the 3D wind simulator in Unity 3D virtual reality. When the fan is in use, the analog data received from the flex sensor attached to the fan triggers the 3D wind simulator in Unity 3D virtual reality. This has been visually illustrated in Fig. 37.

C. The e-textile hand-fan interface is perceptually coupled to the wind simulator in Unity 3D virtual reality or digital representations (rep-d), these can never been seen apart within the system of the TUI.

D. When in use the hand-fan interface literally represents the 3D wind simulator wind in virtual reality, in that sense embodying the digital state.

Distinguishing physical properties of Tangible Artifacts with respect to Prototype 4. are discussed below.

A. Physically embodied: The 3D wind simulator in Unity 3D virtual reality is embodied within the hand-fan interface. When in use the interaction result in corresponding triggering of the 3D wind simulator.

B. Physically representational: The representation here is literal, a hand-fan when in use generates wind and represents a 3D wind simulator in Unity 3D in virtual reality.

C. Physically manipulable: These artifacts are made of fabric and can be folded, opened and closed as illustrated in Fig. 38.

D. Spatially reconfigurable: These artifacts can be spatially reconfigurable in 3D physical space and can be rotated freely as illustrated in Fig. 38.

Discussion Active Touch

Prototype 4, describes an e-textile fan interface that can be opened and closed and fanned, and can have various spatial arrangements. In this prototype, the interaction is opening and closing of the fan rather than the exploration of its material surface.

Discussion Haptic Visual Overlap

Haptic visual overlap has been demonstrated through Fig 38. interaction with e-textile fan interface results in corresponding change in the 3D wind simulator in Unity 3D virtual reality.

6.4.3 Prototyping

Gesture 'Swing'

This interface uses an e-textile flex sensor that has been attached to the body of the fan (Fig. 39). When that fan is in use (i.e. swinging from side to side) the data received from the flex sensor is used to control a virtual wind generator in Unity 3D virtual reality.

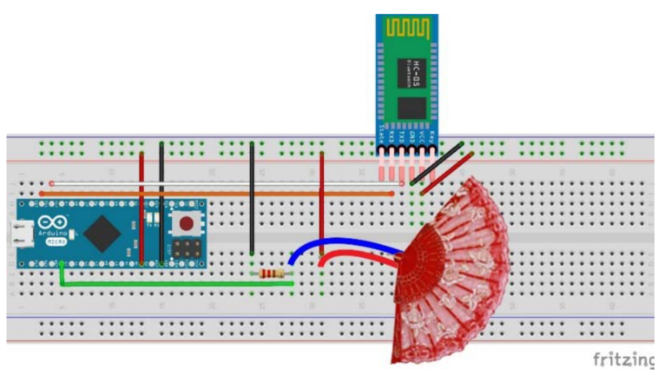

Fig.39 Bluetooth HC05 module with Arduino Micro and an e-textile hand held fan for Unity 3D VR on Samsung S8 Android mobile device.

E-textile interfaces with Bluetooth capability were created using an HC-05 Bluetooth module, as described in Fig. 39. These interfaces work with localized Unity 3D virtual reality apps on Samsung S8 mobile. I used a mobile device with Oculus VR headset to access 3D virtual assets that were controlled through these e-textile interfaces (Fig.40)

The first step of making the HC-05 Bluetooth connector was to make it work with Windows 10 to control assets within Unity 3D using the serial port and then moved on to doing the same with a Samsung S8 Android device.

Fig.40 Oculus Gear VR and VR Fabric asset.

(Left) VR (Samsung S8 + Samsung VR gear) Controlling Unity 3D fabric asset in virtual reality (Right) on Android platform using HC-05 Bluetooth e-textile Hand Fan interface.

6.5 Prototype 5. Squishy Ball Interface

6.5.1 Prototype Description

Prototype 5. Describes a 3D sphere asset being controlled and represented by an e-textile interface that incorporates textile pressure sensors within a ball. In this prototype the intangible representation is a 3D deformable sphere asset in virtual reality. In this prototype the squishy deformable character (haptic compliance) of the material is explored.

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Fig.41a   Prototype 5.A
Interactive tangible e-textile ball interface
Control +Physical Representation (Control+ rep-p)

Fig.41b
Intangible representation (VR asset)
Digital Representation (rep-d)

Textile pressure sensors made of conductive wool have been placed within this interface, and the e-textile takes the shape of the ball thus easily allowing it to be incorporated within the interface.

Fig.42 Squishy ball interface and 3D virtual sphere asset.
Image shows interaction with physical ball interface and corresponding effect on the deformation of the virtual 3D sphere asset.

This further allows non-obtrusive interaction with the material (i.e. where the sensor inside the interface cannot be felt by the participant).

When compared to the screen-based experience, the virtual reality experience accentuates the feel of the interaction by blocking out other visual distractions in the peripheral vision of the physical space and centers awareness on the deformation of the 3D virtual ball asset in virtual reality (Fig. 43) and the feel of physical interface in hand as it deforms through Active Touch (Gibson 1962). The visual difference is also experienced in being present in the space with the 3D asset as opposed to viewing it remotely though a screen.

Fig.43 Oculus Gear VR and VR sphere asset.

(Left) Samsung S8 + Samsung VR gear, (Right) Controlling Unity3D deformable sphere asset in virtual reality on Android platform using HC-05 Bluetooth e-textile Squishy Ball interface.

The 3D virtual asset is rendered in 3D visual space (i.e. virtual reality head set) vs. a 3D virtual asset being rendered in 2D visual space (i.e. flat screen), this causes the interactions with 3D assets within 3D spaces to be visceral and intuitive instead of cerebral. With the set up as shown in Fig.43 it was possible control an asset in virtual reality using Samsung S8 + Samsung VR gear using e-textile using a Bluetooth enabled object/artifact/interface.

6.5.2 Application of Framework

The physical e-textile squishy ball interface represents and controls a virtual sphere. This is reflected in the deformation of a 3D virtual sphere asset in virtual reality. As the e-textile ball is physically squished, there is a corresponding change in the digital representation of “form” of the 3D virtual sphere asset within the virtual reality space. The suggested interaction and the effect on the 3D asset is described in Fig.42. In this system, physical representation (rep-p) is e-textile squishy ball interface, while digital representation (rep-d) is represented through the graphical deformation in the 3D virtual sphere asset. It can also be said that, the digital rep embodies the characteristic of the physical rep (squishy e-textile ball) and the representation is literal.

Discussion TUI

Prototype 5. describes a 3D virtual sphere asset being controlled and represented by an e-textile interface that incorporates textile pressure sensors within a ball (Fig 41a). Some of the key characteristics of the framework that informed my decision with respect to Prototype 5. are discussed below.

A. The e-textile squishy ball interface (i.e. Physical representations (rep-p)) is coupled to underlying computational model that takes into account mesh deformation in the 3D sphere simulation within Unity 3D virtual reality platform as well as sensor data from the e-textile squishy ball interface that register deformation or change in the shape or orientation of the interface.

B. The e-textile squishy ball interface (i.e. Physical representations (rep-p)) embodies mechanisms for interactive control of the 3D virtual sphere asset. By deforming the form of the e-textile squishy ball interface it is possible to change the form of the 3D virtual sphere asset. This has been visually illustrated in Fig. 42 through a series of possible suggested interactions.

C. The e-textile squishy ball interface is perceptually coupled to the 3D virtual sphere asset or digital representations (rep-d), these can never been seen apart within the system of the Tangible User Interfaces.

D. The stretchable, deformable nature of fabrics (i.e. behavior) allow them to represent semi-solid like 3D virtual entities (i.e. deformable 3D sphere asset). This ability of fabrics to be molded, deformed, and shaped during interaction enable them to embody characteristics of the virtual asset.

After applying the framework, I could question the physical textural quality (haptic compliance) of the e-textile ball interface and the spatial reconfiguration ability of physical ball element, as discussed in Chapter 2.1.2 identifying texture through touch. Here haptic compliance is defined as the objects stiffness or flexibility.

Distinguishing physical properties of Tangible Artifacts with respect to Prototype 5. is discussed below.

A. Physically embodied: The shape and form of 3D virtual sphere asset as illustrated in Fig. 42. is embodied within the shape and form of the physical artifact/interface. The change in the shape and form of the squishy ball interface during interaction result in corresponding change of the 3D virtual sphere asset.

B. Physically representational: The representation here is literal where an interface made of e-textile squishy ball interface represents a 3D visual sphere asset in virtual reality.

C. Physically manipulable: These artifacts are made of soft conductive wool Eeonyx's material (see Chapter 4.2) and materials that allow deformation as illustrated in Fig. 42.

D. Spatially reconfigurable: These artifacts are spatially reconfigurable in 3D physical space.

Discussion Active Touch

In Prototype 5. the stiffness or plasticity of the object is in focus when a finger presses on a rigid surface or squeezes an object with the hand. It is difficult to notice the increased intensity of skin-based sensation, but one is aware of the object's substance and its resistance (i.e. haptic compliance). Likewise, when pressing or squeezing a non- rigid object (a soft ball) the participant is aware of the deformability softness of the substance and not that of their fingers. This phenomenon of awareness towards the deformable object has been leveraged in this prototype to make a connection between the physical and the virtual world (Gibson 1962). This is further amplified by the physical object/artifact/interface being mapped in virtual reality creating a realistic Haptic Visual overlap (Fitzmaurice 1998). The e-textiles interface is an unconventional controller that controls an asset within the virtual space.

Discussion Haptic Visual Overlap

Haptic visual overlap has been demonstrated through Fig 42. Interaction with e-textile interface results in corresponding change in the visual form of the 3D virtual sphere asset in virtual reality. Various squishy ball shaped prototypes were created as a part of this series of prototyping, these primarily use the tactile, tangible and easily manipulative (i.e. displacement) nature of the textile materials to its advantage. These have been discussed ahead in Prototype 5.B, 5.C, 5.D and then in the final Prototype 6.

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Fig.44a Prototype 5.B

Interactive tangible e-textile ball interfaces
Control +Physical Representation (Control+ rep-p)

Fig.44b

Intangible representation (VR asset
Digital Representation (rep-d)

Prototype 5.B Comparing physical material stiffness (haptic compliance) of three different materials to one 3D deformable virtual asset.

To further understand tangible, material softness, stiffness, or malleability (haptic compliance), a prototype was created with three separate ball interfaces, each made from three different materials (i.e. each having different material qualities) but controlling the same 3D virtual sphere asset (3D virtual sphere from Prototype 4.A) one at a time. I noted that there was discrete difference in material feel (haptic compliance) vs. visual 3D asset deformation, when comparing physical material tangibility to the visual counterpart.

Prototype 5.C Comparing physical material stiffness (haptic compliance) of textile material that have three different consistencies to various deformable 3D virtual asset.

To further understand tangible material softness, stiffness, or malleability (haptic compliance), a prototype was created with three separate squishy ball interfaces, each made from the same material (i.e. wool) but each having different haptic compliance, each controlling three different 3D virtual sphere assets, one at a time. This prototype has been set up for testing the nature of haptic compliance of materials and to qualitatively understand if the participants can distinguish between similar stiffness and malleability (haptic compliance) of physical interface and match them to their respective 3D visual deformable assets. The virtual aspect of this prototype was rendered on Oculus Rift VR.

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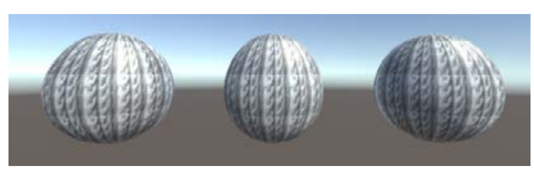


Fig.45a Prototype 5.C

Interactive tangible e-textile ball interfaces

Control +Physical Representation (Control+ rep-p)

Fig.45b Digital Representation (rep-d) (VR asset)

Intangible representation (VR asset)

Digital Representation (rep-d)

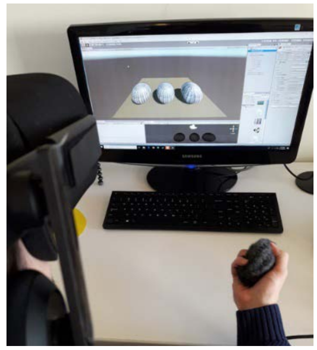


Fig.45c Interfacing with Prototype 5.C

6.5.3 Testing Prototype 5.C

This test differentiates physical haptic compliance (i.e. stiffness and flexibility) of e-textile materials when compared to their 3D visual assets using qualitative analysis in a virtual reality environment.

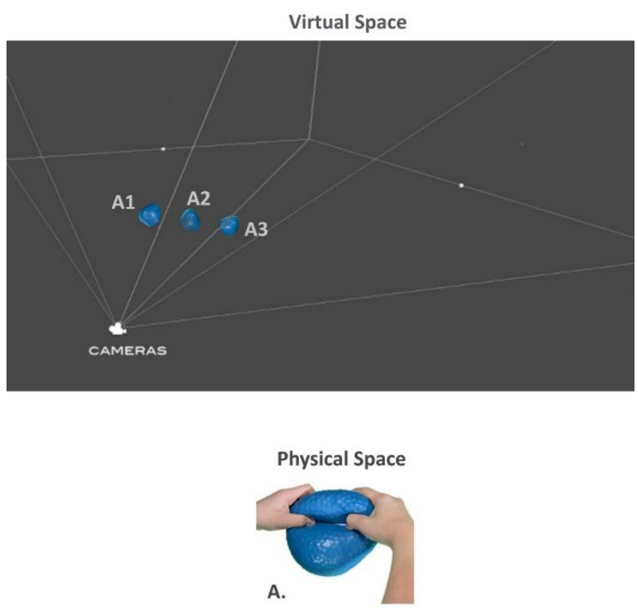


Fig. 46 Test Setup for Prototype 5.C

During this test, different kinds of physical materials (i.e. different degrees of stiffness or flexibility) that create different perceived deformation in 3D virtual visual assets were investigated. It tests the ability of user to discriminate between varying simulated visual deformations in 3D visual assets within a virtual reality setup shown in Fig. 46. Qualitative feedback about interacting with an e-textile interface for virtual reality applications were collected.

The task and procedure is set in a virtual reality environment, the participant manipulates three 3D visual assets with different virtual deformations using e-textile interfaces created during Prototype 5.C. The participant was asked to sort these 3D visual assets with their most preferred choice in ascending order. After the participant completed three rounds of the sorting experiment, qualitative feedback was requested.

For the participants to become used to the e-textile interfaces/objects they were shown cues of how to interface with them before the study began. During the testing process the participant were allowed to freely explore each of these e-textile interfaces with their 3D visual asset for 3 minutes within virtual reality, each before being asked to fill out the feedback form.

Reflections on Prototype Feedback 5.C

This test was designed to understand how stiffness and firmness (i.e. force compliance) of physical materials can be matched to corresponding 3D simulations in virtual reality. Several people were asked to physically interface with e-textile objects and their observations were recorded both verbally and in a written questionnaire.

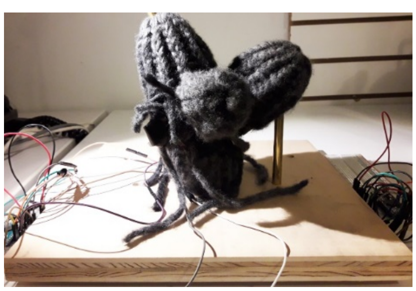
Participants mentioned that the objects in their hand (i.e. e-textile interface) felt “soft” and “spongy”. They also said that the feel of the objects made them want to continue touching and manipulate them. Learning - soft deformable objects encourage active touch (Gibson 1968).

Participants also commented that the corresponding simulation was responsive yet surprising, that it was against their expected perception. Learning - the corresponding graphics in virtual reality did not mimic the change in physical object manipulation. To make an immediate connection with a user it was important to map the simulation to the physical object deformation.

The user tests also revealed that untethered physical objects are more difficult to haptically locate in space. This is due to a lack of depth perception in virtual reality because the placement of the hand in physical space doesn't match the placement of the 3D virtual object.

Prototype 5.D spatial arrangement of three different physical material stiffness (haptic compliance) to create an e-textile interface.

To further promote active touch, the materials and their corresponding 3D visual assets were arranged in physical space (Fig. 47a) and also in virtual reality (Fig. 47b). The spatial arrangement of elements is one of the key characteristics of the physical properties of tangible objects/artifacts/interfaces as discussed in Chapter 2.1.1.



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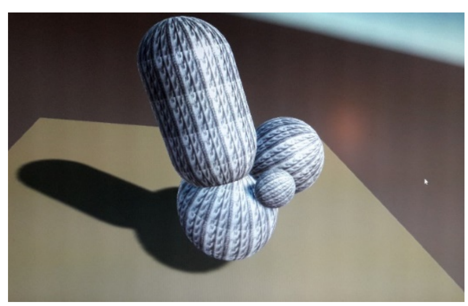

Fig.47a Prototype 5.D

Interactive tangible e-textile ball interfaces

Control +Physical Representation (Control+ rep-p)

Fig.47b

Intangible representation (VR asset)

Digital Representation (rep-d)

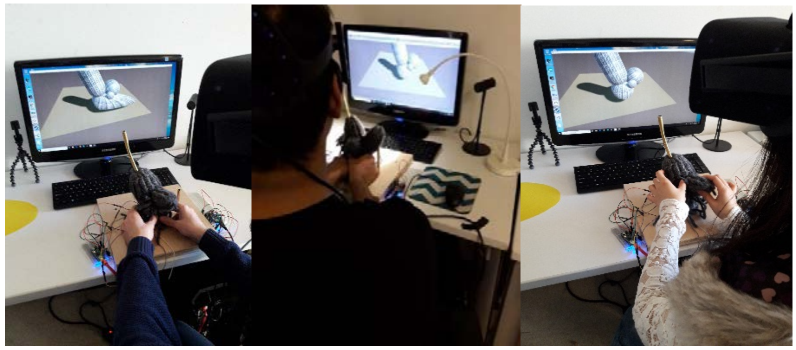

Fig.48 Interfacing with Prototype 5.D

The virtual aspect of this Prototype 5.D was rendered on Oculus Rift VR.

The first round of virtual reality development took place on a Samsung S8 Mobile device on the Android platform, as illustrated in Fig.40 and Fig.43. The 3D visual asset in virtual reality was created in Unity 3D and were loaded on the device. The Unity 3D file acted like a localized app that could be accessed through Oculus Gear VR headset. I was able to use up to 3-4 sensor inputs using the HC-05 Bluetooth module that was connected to the mobile device through the Bluetooth to the phone device.

The second round of virtual reality development took place on the Oculus Rift device. This allowed for faster virtual reality development because it is a far robust system. The microcontroller connects to the PC via USB which provided continuous and significantly improved data transfer and improved response time.

6.5.4 Testing Prototype 5.D

This test differentiates physical, haptic, compliance (i.e. stiffness and flexibility) of e-textile materials. Using qualitative analysis in a virtual reality environment, this test compares the stiffness of physical haptic objects to deformation of 3D visual assets.

Utilizing reflections about material softness/stiffness and the placement in objects in physical space from the previous prototyping setup, I created another prototype where users interacted with physical objects that possessed different force compliances. These objects were stacked in physical space in a cactus-like configuration (Fig 47a). This arrangement created a continuous surface that users inspected with their hands. The virtual object visually represented the physical object and the user was asked to compare the various physical stiffness of the e-textile interface to the 3D visual objects in virtual reality.

Reflections on Prototype Test 5.D

During the testing of this prototype I realized it was tough for the user to move from one object to another because the individual, physical, objects were tightly packed against each other. Hand dexterity in physical space is difficult if the 3D virtual object position and placement is not well separated. Also, the users commented that manipulating objects in virtual space without the presence of a virtual hand was difficult, but manageable.

6.5.5 Prototyping

Gesture 'Squeeze'

These prototypes explored creating sensors from soft, conductive wool Eeonyx's material. The conductive wool was either encased or glued to a stretch knit fabric. Fig. 49 shows an image of a stretchable knit fabric with two patches of conductive wool adhered on the surface using industrial glue. Adhering conductive wool on the surface of fabric created a point of resistance, and by having multiple such points of resistance built into the fabric using this technique, it is possible to create a resistive e-textile surface that was pressure sensitive. As the top surface of the e-textile conductive wool patch is pressed, pushed or squeezed the resistance within it changes, this creates a change in value of the data recorded. Depending on the intensity of the pressure, the data received from the sensor changes from high to low as noted in Fig.50 Image 3 from the right.

Fig.49 Pressure sensor made from conductive wool and adhered to stretchable knit fabric.

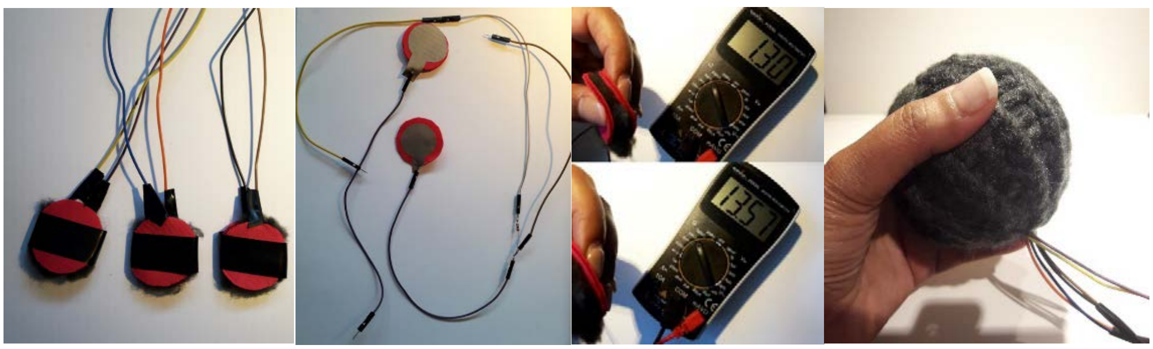

Fig.50 Conductive wool pressure sensor. (Left) Three pressure sensors created by encasing e-wool substrate. (Extreme right) Ball with three sensor inputs.

In another exploration using conductive wool, pressure sensors were created by encasing the conductive wool between two conductive surfaces. The conductive surface was made using conductive iron-on fabric as shown in Fig. 50, the second image from the right. When pressure is applied to the sensor, the resistance value changes. Higher pressure results in lower resistance values while lower pressure results in higher resistance values.

The data received from the sensor manipulate a 3D deformable sphere asset in Unity 3D virtual reality platform. These pressure sensors have been created so that they can be easily incorporated within soft moldable fabrics. Due to their soft material nature, these sensors can easily be incorporated within fabrics, such that, during interaction the user cannot to determine they are present. This leads to a more cohesive and non-obstructive interaction.

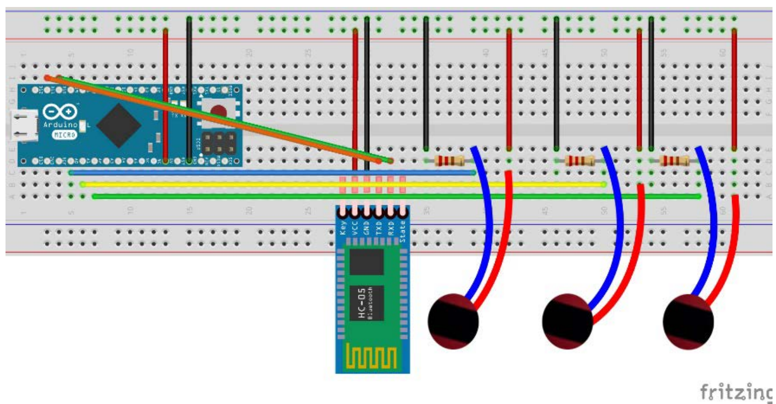

Fig. 51 Three pressure sensor input and HC05 Bluetooth module

At this stage of prototyping, I had shifted to creating interfaces with multi sensor inputs. This is illustrated in the setup in Fig.51. where three sensors created from conductive wool can be seen attached to the Bluetooth setup. Prototype 5.C and Prototype 5.D use Oculus Rift setup so the sensor data is directly fed using USB.

In conclusion it can be said that a series of e-textile interfaces were made during this project. These were created using the framework of Tangible User Interfaces, the theories of Active Touch and Haptic Visual overlap. The e-textile interface went through an explorative phase where, I worked and created several ideas and then prototypes of them. Further, prototype “Boomerang” (Prototype 6.) reflects a cumulative understanding of how the theoretical framework was applied while using the Research through Design methodology in creation.

6.6 Prototype 6. Boomerang

6.6.1 Prototype Description

Prototype 6. describes a series of e-textile objects/artifacts/interfaces created from a combination of conductive materials (i.e. soft conductive wool Eeonyx material) and conductive and non-conductive yarn. These objects/artifacts were be made from knitted fabrics that allow easy deformation and soft interactive surfaces that amplify the haptic experience.

Fig.52 "Boomerang" Prototype 6. Setup

They were displayed in an interaction space (i.e. table) Fig. 48. The objects/artifacts/interfaces in physical space was mapped in virtual reality as 3D virtual assets (i.e. similar to Fig. 46a and 46b). While experimenting with the spatial arrangement of objects/artifacts /interface, the arrangement of material that leads to more exposed surface areas seemed to promote better interaction. The e-textile objects/artifacts/interfaces were constructed from feedback received during testing.

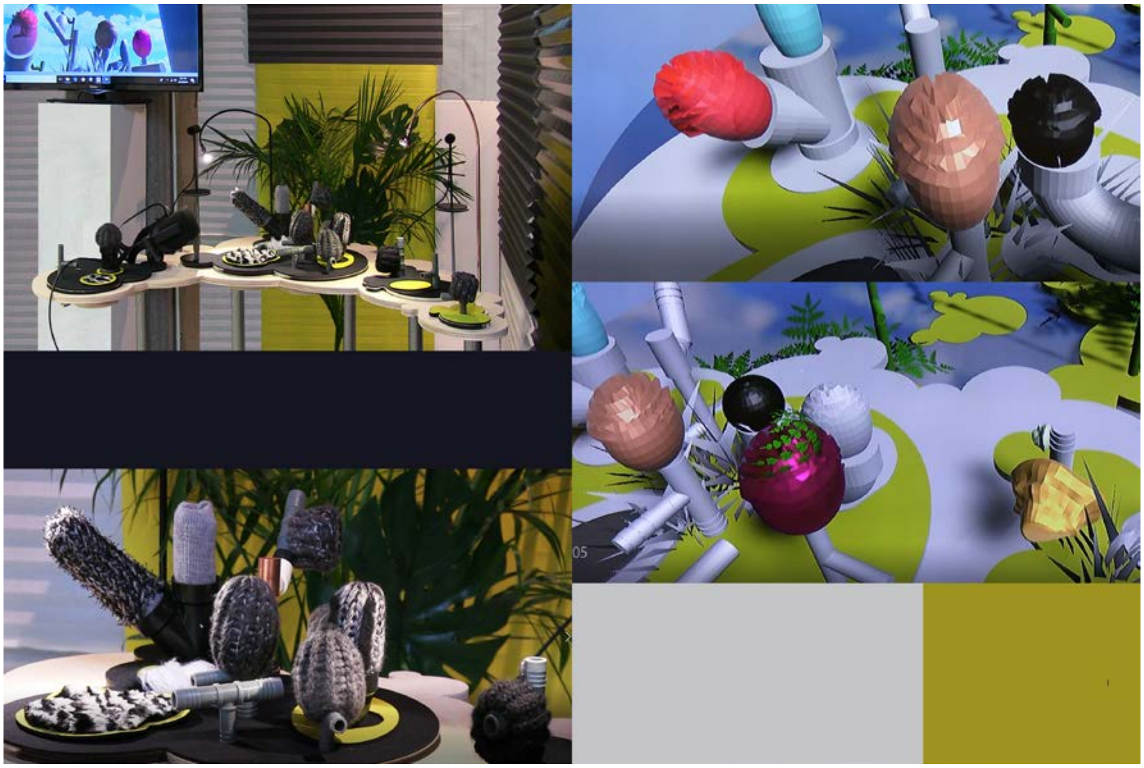

Fig.53a “Boomerang” Prototype (left) Physical object details; (right) Virtual environment

The physical interface in prototype Boomerang, is a soft, wool, knitted fabric that’s cast over sponge and deformable rubber. Users can easily manipulate this textile interface using their hand and as a result the interface can adopt varied shapes. The soft sensors embedded within the textiles can take the form of various objects and as the user presses and deforms the shape, the sensors process the changing shape and form. A microprocessor reads the collected data and then uses the data to manipulate the actual, deformations onto the 3D visual asset in virtual reality.

In prototype Boomerang, various kinds of touch have been explored using the resistive properties of e-textiles. These are shown in the following illustrations.

A. “Grab” type interaction

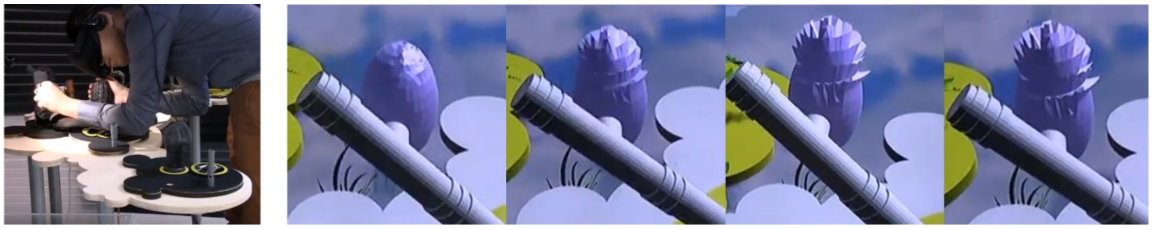

Fig.53b “Boomerang” Prototype (left) “Grab” interaction with physical interface; (right) corresponding real-time change in virtual environment

To enable a “grab” interaction, the user tightly grasps the textile object, causing the 3D virtual asset to bloom. In this case, the virtual object expands because the e-textile snugly fits the shape of the physical object.

The textile sensor is made from conductive wool that has been sandwiched between two strips of conductive fabric. Each time the physical interface is tightly grasped, change is recorded in the resistance of the sensor and the received data deforms the virtual asset.

B. “Squish” type interaction

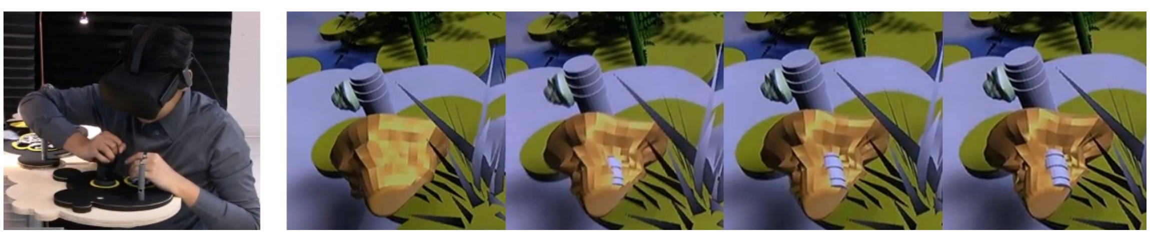

Fig.53c “Boomerang” Prototype (left) “Squish” interaction with physical interface; (right) corresponding real-time change in virtual environment

In a “squish” interaction, the fabric loosely adheres to the physical object and leaves room for more deformation. The virtual object responds to the changing shape of physical object. In the above example, the virtual asset contracts.

C. “Pat” type interaction


Fig.53d “Boomerang” Prototype (left) “Pat” interaction with physical interface; (right) corresponding real-time change in virtual environment

In a “pat” interaction, the user explores a flat, soft, surface. The virtual asset can be deformed and in this example, when the fabric is pressed the 3D asset splatters.

The 3D visual assets in virtual reality have been designed to react to objects in the physical interface. Physical objects in the interface are augmented with computational capabilities that allow for data to be accessed from them and then this data can be used to control assets in the virtual reality space. The virtual reality experience accentuates the feel of the interaction by blocking out other visual, peripheral distractions and centering awareness on the changing asset.

In the virtual space, the asset can be deformed. For example in the “Grab” interaction, the 3D asset grows. It’s important to note that this change, while triggered in the actual world, is only evident in the virtual world. In other words, the virtual asset grows while the e-textile remains the same size. However, in the “Pat” interaction, both the 3D visual asset and the physical asset deform in parallel.

Fig.53e "Boomerang" Prototype (top) Virtual table layout; (bottom) Physical object layout

The shape and the height of the table were built for human interaction. The user sits or stands in front of the table and explores the interact-able objects present on the table surface. The table is arc-shaped and this allows for bodily movement of 110 degrees from right to left and left to right.

In the previous prototypes the physical objects were untethered and could easily be spatially reoriented and arranged in 3D space. In prototype Boomerang, the objects are fastened to a stationary table surface. This gives the user a better understanding of the physical position in the virtual environment because the physical prototype (i.e. table interface) is mapped to the virtual table (i.e. 3D visual asset). Tethering gives the user a better understanding of the tangible object placement and makes the grasping objects easier and the interaction more responsive.

6.6.2 Testing

Using qualitative analysis in a virtual reality environment, this setup compared the e-textile’s stiffness and flexibility to their 3D visual assets. This setup evaluated if a relationship could be established between the physical object and the virtual objects through haptic inclusion. I created an identical 3D, virtual, model of the physical table. The textile objects on the table were computationally augmented with soft e-textile sensors that allowed for change and deformation.

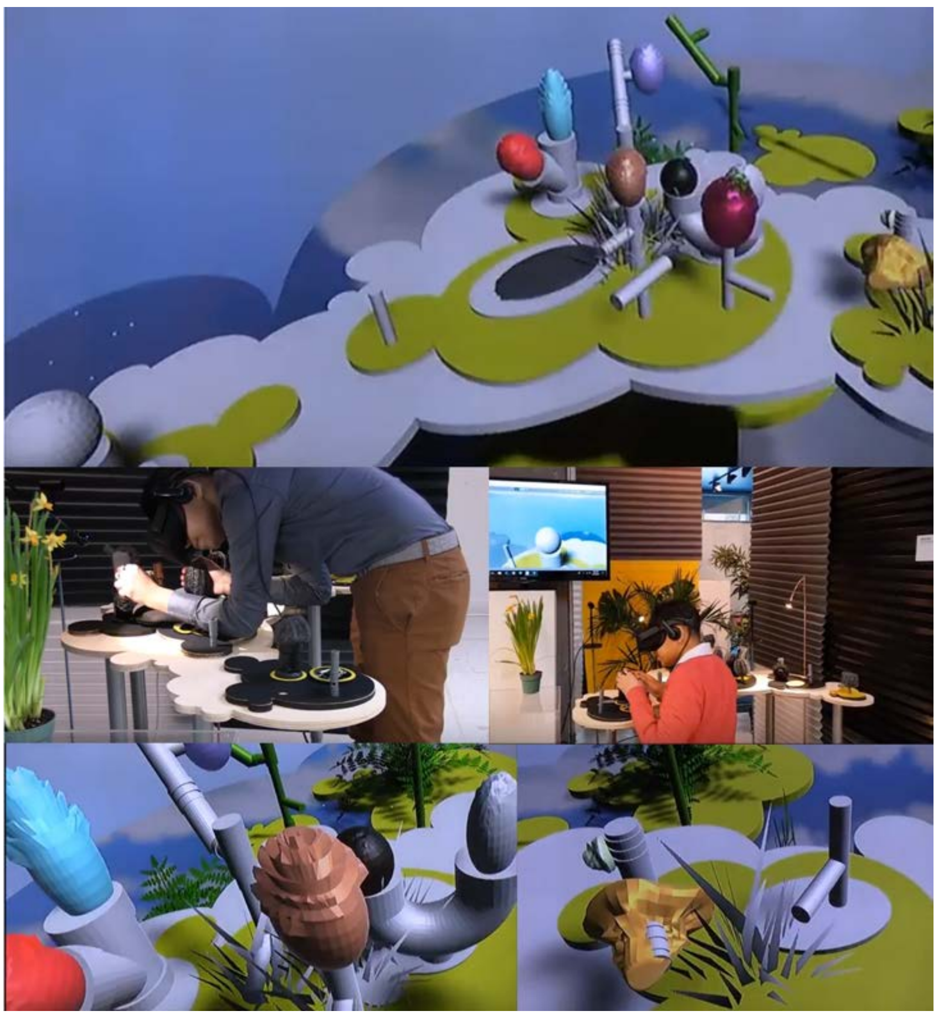

Fig.54 Testing Prototype Boomerang

I tested different kinds of physical materials (i.e. different degrees of stiffness or flexibility) and their ability to create variances in perceived deformations. I also tested a user's ability to discriminate between various simulated deformations. My setup is shown in Fig. 54.

During this test, different kinds of physical materials (i.e. different degrees of stiffness or flexibility) that create different perceived deformation in 3D virtual visual assets were investigated. It tests the ability of user to discriminate between varying simulated visual deformations in 3D visual assets within a virtual reality setup shown in Fig. 54. Qualitative feedback about interacting with an e-textile interface for virtual reality applications was collected. This prototype also explored various kinds of touch as described in Chapter 6.6.1.

Before the study began, participants were shown cues about how to interact with the e-textile interfaces. During the testing process participants freely explored each of the interfaces with their 3D visual asset for 5 minutes before being asked to fill out the feedback form.

Reflections on Boomerang Feedback

Initial observations indicated that users were intrigued with the table and wanted to know the table's purpose. A few participants mentioned that they instinctively wanted to "touch" the objects on the table and that the table was inviting.

User number one mentioned that that the physical object was almost "anti-climactic" to the virtual table, because the physical objects were soft but in the virtual world they were spiky. They were very intrigued with the visual experience in virtual reality especially when reacting to the grasp versus the animation of the 3D visual assets. User one stated, "the animation is in direct response in virtual reality. That is super cool. It's almost like the notion-every action has a reaction". They also felt that the virtual object and the physical objects were "practically the same".

User number two described the objects on the table as having different textures and mentioned they were like “soft toys” (learning- this resonated with the feedback I received in Prototype 5.D). They described the visual experience as very calming and like being in the “clouds”. They also found a correlation with the physical objects and the virtual experience.

The third user said the physical interface “reminds me of Mickey Mouse ears and computer mouse pads. The furry stuff reminds me of kid’s toys. The shape of the table reminds me of the clouds.” This was parallel to my own thinking and partly my impetus to create this work. The third user also commented on the fact that it was inconvenient to see their own hands in virtual reality.

Summary

Prototype Boomerang considerably improved user’s hand movement. Compared to previous prototypes, 5.C and 5.D, Boomerang users freely navigated from one interactive object to another. Boomerang users also took full advantage of the arcing table and turned from end to end, in an arc of 110 degrees. This mobility expanded users sense of freedom and made the virtual experience more realistic, especially because the user could view the 3D assets up close and therefore have spontaneous interaction with them. This spontaneity and magnification was possible because the physical table was mapped to, and coordinated with, the 3D virtual asset. Such coordinated mapping allowed users to explore the tangibility of each object and gauge its connection and response to the parallel asset in virtual reality. Users were fascinated and intrigued by this overlap between the physical object and the visual experience.

8. Conclusions and Future Directions

Summary

Over the last decade, there have been numerous efforts in material research that have enabled interactive textiles within digital spaces. Most work focuses on integrating sensors for planar touch gestures such as swipe or tap, and thus do not fully take advantage of the flexible, deformable and tangible material properties of textile. The resulting work aims to address better interfaces in Human Computer Interaction that can be further applied to design within virtual reality.

At the current time it is limited to hand-held controllers, these devices are built to execute a set of instructions activated through touch. Human Computer Interaction in this project is very different, since the interface and the virtual reality, intuitively connect or the interface acts as an embodied object taking on certain character of the 3D visual asset in virtual reality. This kind of interfacing lends itself to a different genre of virtual reality games, where game play becomes more intuitive rather than instructional.

The project connects the intrinsic tactile quality of touch and the tangible aspects of a material to a visual counterpart. This aspect can be used in cognitive therapy where phobias (Carlin, Hoffman and Weghorst 1997) and sense-based disorders that are being cured using virtual reality and tactile objects. Virtual Reality is also being considered an effective way of teaching skills that are hard to practice in the real world. Including haptics element to virtual reality now allow medics to train without having to test out their basic skills on an actual patient.

During this thesis, various explorations were created with the aim of producing more responsive e-textiles. A review of the research questions and my findings are provided here.

1. *How might the physical affordances of textiles be used as part of a tangible user interface for a virtual reality experience?*

In the various prototypes, textile materials (i.e. yarns, fabrics) have been crocheted and knitted and physically worked upon to create e-textile materials that can be cast over sponge and deformable rubber to form the physical interface conducive for interaction using the hands. The e-textile materials can take the shape of objects and also allow the user to manipulate them using their hands freely. The soft sensors embedded within the textiles takes the shape and form of the objects and follow the path of deformation as the user presses or deforms them. The data collected from the deformation of these textile objects is read by a microprocessor and is used to manipulate 3D virtual visual asset in virtual reality. The physical object deformation is mapped to the virtual asset transformation.

2. *How can the conductive and resistive properties of electronic textiles be used to detect different kinds of touch?*

Various kinds of touch have been explored during the creation of various artifacts/objects and interfaces during the course of this project. These include “grab”, “squish”, “drag”, and “pat”. These have all been constructed through the use of employing e-textile sensors embedded within physical objects that have certain shape and size and that promote active touch. The respective shape of the physical object entertain certain kind of touch and the interface has been designed to exploit this tendency.

3. *How can 3D visual assets in virtual reality respond to changing conditions of objects in the physical world?*

The 3D visual assets in virtual reality have been designed to react to objects in the physical interface. Physical objects in the interface are augmented with computational capabilities that allow for data to be accessed from them and then this data can be used to control assets in the virtual reality space.

While previous prototypes showed some promise in integrating e-textiles within virtual reality worlds, creating physical interfaces was difficult for several reasons. The main problem was the number of sensors that could be incorporated into the interface. In early interfaces like the Knitted Disks, the Hand Fan, and the Squishy Ball, I placed 1-3 sensors and used a Samsung S8 device and Gear VR setup. However, in my final interface, Prototype Boomerang, I placed twenty sensors and these additional sensors affected the frame rate. Additional controllers required additional sensors that led to negatively affect the frame rate and cause distortions in the viewing experience in virtual reality. I solved this problem by using fewer sensors within each physical object and placing them in a manner that would have maximum impact during interaction.

Reflections

Some reflections in this space are to do with views on ubiquitous computing and its influence on virtual reality in the future. Computing is a ubiquitous entity that collects information on the current human condition. It's an insatiable data-collecting machine tracking our likes and dislikes, what we buy and what we think about what we buy, what we watch and what games we play, where we travel and even what we eat. We often think of machines as teaching us, but in reality, it's the opposite. Not only are we are complicit in their data collection, but by creating devices that easily transmit and share data, we are teaching computers how to process and retain information about us.

E-textile sensors can be networked easily and this ease highlights a proliferated, but nascent, visual intelligence ready to be taught, molded, and shaped. In the future of embedded technologies it will be challenging to differentiate electronics from every day, non-computational, objects. Virtual reality will soon exist as a parallel and alternate reality where people will spend large amounts of time in a digital created and curated environment. These environments will be efficient spaces to work, shop, entertainment, and coordinate with other people and obviously we will access them through our exiting physical environment.

Future Directions

Moving forward, I am particularly interested in developing my work in the construction of e-textile sensors and actuators that are built into the structure of the fabric instead of those that are externally applied to the surface of the textile material. I am also interested in aspects of social computing with fabrics where the incorporation of cultural identity of textiles will play a larger role in digital spaces. I would like to further continue my work with Tangible User Interfaces and on the relationship of the object/artifact and its embodiment in digital spaces and also apply my learning on haptic inclusion in VR to other sense based interactions within this space.

In conclusion it can be said that the physical interactions within virtual reality spaces are predominately through hand-held plastic controllers, featuring buttons and force-feedback cues such as vibration. This project attempts to connect the user and the virtual space via haptic links. By utilizing controllers that are soft, touch-based, interfaces, users can control 3D visual assets in virtual reality and foreground sense-based experiences in a virtual space. Haptics influence virtual reality spaces in a myriad of ways. Passive haptics can be computationally enabled and specifically designed to react to touch. After user testing and qualitative feedback, Prototype Boomerang successfully proved that the connection between virtual space and physical space is possible. Boomerang also proved that users of virtual reality have richer and more impactful experiences when haptic input and experience is integrated into their virtual reality experiences. With the addition of haptic input and control users reported that they explored space better, and that were able to have spontaneous real-time interactions.

Certainly, the days of rigid plastic controllers with simple and limited feedback are numbered. As the virtual reality experiences grow more dimensional and sensorial in their attempt to replicate and augment real life, users will demand controllers with increased haptic capabilities and an expansive range of intuitive and powerful options. Boomerang is the beginning of such an exploration. Textiles have been a part of society for centuries and Boomerang is a first and valuable step into taking advantage of a user's inherent familiarity with fabric and using that knowledge to deepen, expand and enrich the virtual reality experiences. By combining the known with the unknown, a third level of knowledge is created and this liminal space is rich in possibility for both virtual reality developers and virtual reality consumers.

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Appendix A. Test Questionnaire and Answers 5.C

Verbal questions during the Test:

A. Describe how does the physical object (A) feel to touch?

B. Describe the visual experience?

C. Which of the visuals (A1, A2, A3) is closest to the feel of the physical object (A)?

Written questionnaire after the Test:

A. Does the virtual represent the physical objects in the way it "looks"?

B. How close is the what you "feel" to the virtual experience?

C. Describe in few words the tangible qualities of the physical interface?

Feedback on Prototype 5.C

Feedback 1.

The objects in the hand feel "soft" and "spongy". It feels larger than the object in hand. A2 was closest to the physical object. The object in the hand and the visual looked very similar. The graphics can be improved, it was a little inconsistent with the hand movement. The softness of the material makes me want to touch it more and more.

Feedback 2.

The ball is "squishy" and good to touch. The space is very empty and strange, the visuals look like blobs. A2 is closest to the ball. It is quite similar but the graphics should be improved, it is not very enjoyable. The squishy feel and the animation do not match that well, it can be made better. The ball is "soft" and "toy like".

Appendix B. Test Questionnaire and Answers 5.D

Verbal questions during the Test:

A. Describe how does the physical object feel to touch?

B. Describe the visual experience?

C. Are the visuals close to the feel of the physical objects?

Written questionnaire after the Test:

A. Does the virtual represent the physical objects in the way it “looks”?

B. How close is the what you “feel” to the virtual experience?

C. Describe in few words the tangible qualities of the physical interface?

Feedback on Prototype 5.D

Feedback 1.

The interface was described as a medium-to-hard stuffed animal that is not too soft and not too hard “medium squishy”. It was also described as a warm sweater. The virtual objects were described to be close in “look” but it was suggested that the overall visual impact could be improved. Not much differences were made between the 3D visual assets.

Feedback 2.

The objects in virtual reality were described to have a very quick response to squeezing actions and response to different pressure strength. “It’s very responsive but it still needs to develop, the effects in the software can be made more accurate.” The simulations were described as being “bit beyond the physics”. For example, when the interface was squeezed it was expected that the 3D virtual asset would shrink in the same direction as the object.

The appearance of the 3D visual asset was described pretty much the same as the physical object, but that the texture can be improved and made more fluffy. The experience overall was described as very responsive and interesting.

Feedback 3.

The physical touch was described as delicate and soft, that encouraged touching “again and again” also the form was described as being constructed in a manner that “created a relationship with the hand”. The virtual reality experience was described as being a good visual impact but that more possibilities could be explored in terms of 3D asset deformation “It could be made more reactive and responsive.” Overall it was described as a connecting experience.

Appendix C. Test Questionnaire and Answers Prototype 6

A. Describe how does the physical object feel to touch?

B. Describe the visual experience in virtual reality?

C. How close is what you feel (i.e. physical object) to the virtual experience?

Feedback on Prototype Boomerang

Feedback 1.

A. They feel like almost anti-climactic to the virtual world. As in real life they're soft but in the virtual world they're spiky. Also doesn't remind me of anything.
B. The visual experience is intriguing, based on the pressure points of the physical objects, the animation is in direct response in VR. That is super cool. It's almost like the notion, "every action has a reaction": this is a direct relation to this saying.
C. B and C are connected. They're practically the same.

Feedback 2.

A. The objects on the table have different textures. It feels like playing with “soft toys”.
B. The visual experience is very peaceful, it is very calm in the clouds. I like it.
C. The objects on the table and the visuals in virtual reality are nearly the same when they are touched. The response is very good.

Feedback 3.

A. It reminds me of Mickey Mouse ears and computer mouse pads. The furry stuff reminds me of kid’s toys. The shape of the table reminds me of the clouds.
B. The very good feeling place, although I may fall through the ground. It feels like floating in the cloud.
C. On touching the object, feels very strange at first but I got used to it very fast and also it took a while to understand where my hand were because I could not see them in virtual reality.

Appendix D. REB Approval Letter

March 28, 2018

Kate Hartman
Faculty of Liberal Arts & Sciences & School of Interdisciplinary Studies
OCAD University

File No: 101255
Approval Date: March 28, 2018
Expiry Date: March 27, 2019

Dear Kate Hartman, Ms. Shreeya Tyagi,

The Research Ethics Board has reviewed your application titled 'Electronic Textile as Tangible Interface for Virtual Reality'. Your application has been approved. You may begin the proposed research. This REB approval, dated March 28, 2018, is valid for one year less a day: March 27, 2019. Your REB number is: 2018-29.

Throughout the duration of this REB approval, all requests for modifications, renewals and serious adverse event reports are submitted via the Research Portal.

Any changes to the research that deviate from the approved application must be reported to the REB using the amendment form available on the Research Portal. REB approval must be issued before the changes can be implemented.

To continue your proposed research beyond March 27, 2019, you must submit a Renewal Form before March 20, 2019. REB approval must be issued before research is continued.

If your research ends on or before March 27, 2019, please submit a Final Report Form to close out REB approval monitoring efforts.

If you have any questions about the REB review & approval process, please contact the Christine Crisol Pineda

If you encounter any issues when working in the Research Portal, please contact our system administrator

Sincerely,

Nancy Snow
Chair, Research Ethics Board