From Illusions to Beyond-Real Interactions in Virtual Reality

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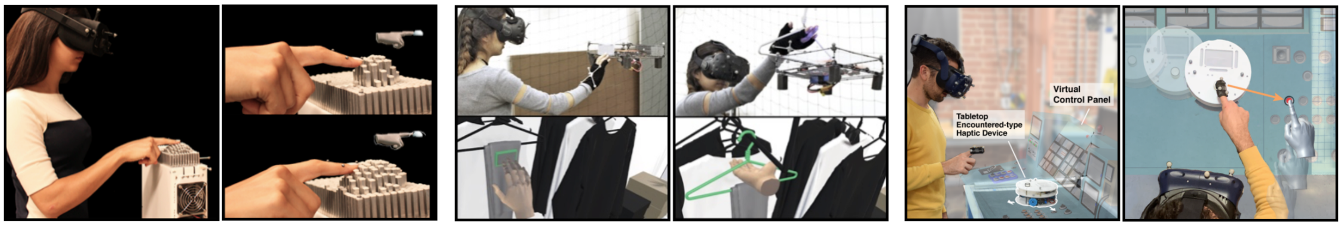

Figure 1: Visuo-haptic illusions used to improve the perceived performance of encountered-type haptic devices in virtual reality. Left: using control/display ratio modification to improve the resolution of shape displays. Middle: using retargetting to improve the position accuracy of drones. Right: dynamic retargetting used to improve the reachability of tabletop robots.

ABSTRACT

Despite recent advances in technology, current virtual reality (VR) experiences have many limitations. When designing VR interactions, we can leverage the unique affordances of this virtual medium and our ability to programmatically control the renderings to not only overcome these limitations, but also to create new interactions that go beyond the replication of the real world. In my dissertation, I seek to answer the following research questions: How can we utilize the unique affordances that VR offers to overcome the current limitations of this technology? How can we go even further and design mixed reality interactions that leverage these affordances to extend our experiences in the real world? In my work, I approach movement-based VR interactions from a sensorimotor control perspective, carefully considering the plasticity and limits of human perception. To answer the first research question, I explore various visuo-haptic illusions to overcome the limitations of existing haptic devices. In my ongoing work, I am building tools that help researchers and practitioners design and evaluate novel and usable mixed reality interactions that have no real-world counterparts.

CCS CONCEPTS

• **Human-centered computing → Virtual reality**; **Interaction design theory, concepts and paradigms**.

KEYWORDS

virtual reality, visuo-haptic illusions, sensorimotor system, optimal control theory, reality-based interactions, beyond being there

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1 INTRODUCTION

In recent years, virtual reality has gained popularity, largely due to the advances in technology and the proliferation of commercially available VR hardware. However, current VR technology has many limitations, such as the users' inability to locomote freely and receive realistic haptic feedback when interacting with virtual objects. By embracing the possibilities that VR offers, beyond replication of our real-world experiences, we can design interactions that overcome these limitations. In my dissertation, I explore such VR interactions by leveraging one of the main affordances of VR, which is intercepting the user's sensorimotor loop and programmatically overwriting the real-world sensory signals by those generated in the virtual world. I demonstrate that by designing such interactions we can **not only overcome the limitations of VR technology, but also overcome the limitations of our current reality**.

The idea of leveraging VR beyond the replication of reality dates back to the early days of this technology. In a 1965 article, "The Ultimate Display," Ivan Sutherland proposed that "there is no reason why the objects displayed by a computer have to follow the ordinary rules of physical reality with which we are familiar" and that "such a display could literally be the Wonderland into which Alice walked" [36]. Over the years, other researchers have shared a similar perspective and have highlighted potential benefits of designing VR interactions beyond reality, including for improving human performance [22] and making interactions more efficient, ergonomic, and accessible [19]. For example, the Go-Go Interaction is an arm-extension technique that stretches the users' arm during reach, enabling them to grasp and manipulate distant objects [26].

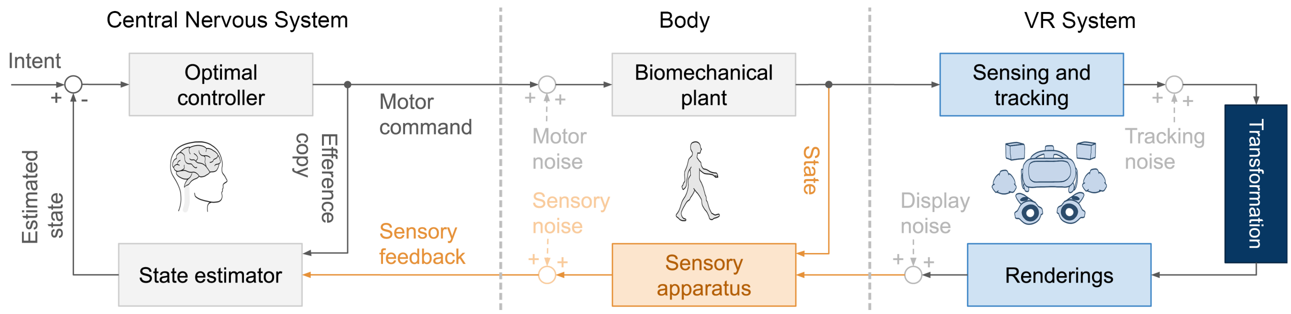

Figure 2: Flow of control signals in movement-based interactions through the central nervous system, body, and VR system.

In "Beyond Being There" (1992) Hollan and Stornetta made a parallel argument during the early days of telecommunication technology and computer supported collaborative work. They argued that when comparing telecommunication to face-to-face communication "the imitation will never be as good as the real thing. This is true by definition if one is strict in using the old medium as the standard of measurement . . . requiring one medium to imitate the other inevitably pits strengths of the old medium against weaknesses of the new" [17]. They presented a framework around needs, media, and mechanisms, "to ask the question: what's wrong with (physically proximate) reality?" and explore new mechanisms that leverage the strengths of the new medium to meet our needs [17].

In my dissertation, I make three main contributions towards similar goals. In Part I, I describe virtual reality interactions through the lens of sensorimotor system and optimal control theory, as transformations applied to tracking and sensing inputs from the real world (figure 2). I group the design of VR interactions into three categories: reality-based, illusory, and beyond-real interactions. I conduct a survey highlighting that illusory and beyond-real interaction designs offer many opportunities that remain underexplored. I argue that this sensorimotor control perspective is key in addressing the challenges around designing novel movement-based VR interactions and understanding which transformations are usable.

In Part II, I explore illusory interactions to overcome one of the current limitations of VR experiences: haptics. Despite the recent advances in audiovisual renderings, haptic rendering has not reached the same level of realism and remains one of the main limitations of current virtual experiences, as users are unable to manipulate virtual objects in the same way they interact with real ones. VR affords unique ways of intercepting users' sensorimotor loop and manipulating their sense of proprioception, as users are unable to see their real body, and arbitrary mappings can be created between their movements and the rendering of their virtual body. We can leverage this affordance as well as the human perceptual limits to improve the perception of haptics in VR. I investigate perceptual manipulations that improve the perceived resolution of shape displays [1], position accuracy of drones [3], and reachability of tabletop robots [13] when used as encountered-type haptic devices.

In my ongoing work, Part III, I am exploring *beyond being real*, a framework for the design of interactions that push past subtle illusions and create novel remappings in spacetime to overcome the limitations of our real-world experiences. While in VR we can arbitrarily remap the sensory feedback users receive upon acting on the world, only certain remappings can be learned by users and lead to sensorimotor adaptation. I am studying what makes certain VR interactions beyond reality usable from a human sensorimotor control perspective and building a design tool for researchers and practitioners. Designing interactions that don't mimic reality could be beneficial for allowing users to perform many tasks (expressive power) across different applications (versatility) and to do so rapidly (efficiency), without fatigue or risk of physical injury (ergonomics), and using a varied range of abilities (accessibility) [19].

2 PART I: A SENSORIMOTOR PERSPECTIVE

In my work, I focus on movement-based VR interactions [12] and action execution [23] (p. 40). Human performance may be modelled at various levels of behavior: skill-based, rule-based, and knowledge-based behaviors [27]. Optimal Feedback Control (OFC) theory focuses on skill-based behavior (e.g., catching a ball) and has been used to predict how the human brain plans and controls movement [32] by studying the link between high-level goals and real-time sensorimotor control strategies [38]. This theory suggests that the Central Nervous System (CNS) acts as a feedback controller, continuously converting sensory input into motor output [39] and it does so optimally, based on a performance metric, such as obtaining minimal uncertainty in the state estimate [40].

I situate VR interactions in our understanding of how the central nervous system interacts with the body during movement-based interactions, as shown in figure 2. In this diagram, blocks represent key components, and arrows denote the flow of control signals, clockwise from the top left. The optimal controller outputs motor commands based on the discrepancy between the desired and estimated states [41]. These motor commands lead to movements in the real world that are then subject to body dynamics and the effects of the environment, such as external forces. The VR system includes sensing and tracking devices that capture the users' movements. Movement-based VR interactions can be thought of as transformations applied to these signals captured from the real-world. The human sensory apparatus receives sensory feedback from both the real world and the virtual system (shown in orange). The state estimator receives the sensory feedback through the sensory apparatus as well as an efference copy of the original motor signal [6].

With this framing, VR is a subsystem intercepting the sensory feedback that the user receives from the real world. VR interactions are transformations applied to the real-world movements (captured by tracking and sensing devices) and produce new sensory feedback that is then integrated with the sensory feedback from the real world. While these transformations are often 1:1, there are opportunities for designing transformations that create novel remappings.

2.1 Survey of VR Interactions

Thurman and Mattoon describe different dimensions of VR, including what they call the *verity*, meaning true to life, dimension. They then use verity to denote "a continuum of simulation experiences that range from recreations of the physical world as we know it to depictions of abstract ideas which have no physical counterparts" [37]. Along this continuum, movement-based VR interactions range from interactions with high degree of verity that follow natural laws of the real-world to interactions with low degree of verity that follow novel, original laws [37]. In Part I of my dissertation, I describe three categories of movement-based VR interactions across the verity continuum: (1) reality-based interactions that directly map users' movements, (2) illusory interactions that create subtle remappings between the users' movements and the virtual renderings that remain unnoticed by users, and (3) beyond-real interactions that create novel remappings between the users' movements and the renderings in the virtual world (figure 3). I conduct a survey of VR interactions and describe the different types of transformations applied. While illusory and beyond-real interactions are underexplored, I highlight that they offer many opportunities and discuss the design challenges from a sensorimotor control perspective.

2.1.1 Reality-based interactions. Highly realistic VR environments that seek to replicate our real-world experiences have been used for practical applications, such as training [16, 31] and exposure therapy for treating phobias [25, 29] or post-traumatic stress disorders [18, 30]. These environments also facilitate user interactions that closely resemble interactions in the real world. Jacob et al. proposed the notion of Reality-Based Interactions (RBI) to describe such interactions that employ themes of reality and leverage users' preexisting knowledge of the everyday in VR and more broadly [19]. They highlight the benefits of RBI, including accelerated learning, reduced mental effort, facilitated improvisation, and improved performance, particularly in situations involving information overload, time pressure, or stress. They also note that despite the advantages of RBI, designers may explicitly give up realism to gain desired qualities, such as efficiency [19]. In my work, I explore VR interactions in which designers explicitly give up realism by creating subtle or novel remappings between user inputs and the rendered outputs in VR to overcome the limitations of VR technology and real-world experiences. However, it should be noted that there are many advantages associated with reality-based interactions, and extending interactions beyond reality is not always beneficial.

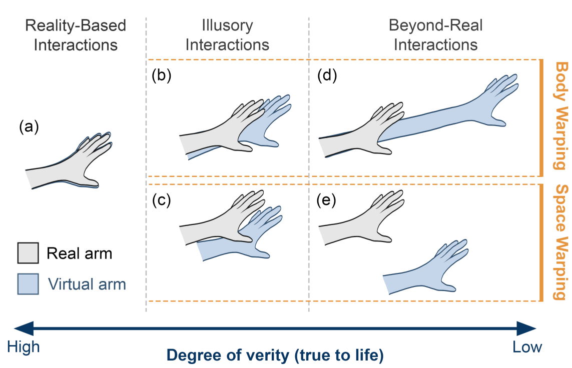

Figure 3: Movement-based VR interactions from high to low degree of verity: reality-based, illusory, and beyond-real. Sensory mismatch created through warping space or body.

2.1.2 Illusory Interactions. As Lanier highlights, our most important canvas in VR is the user's sensorimotor loop [21]. This technology offers a unique opportunity for manipulating users' senses, as arbitrary mappings can be created between the users' movements and the rendering of their virtual body. Movement-based VR illusions are remappings that result in a subtle mismatch between the sensory feedback from the virtual system and the sensory feedback from the real world; however, the discrepancy is below the human perceptual thresholds and is resolved such that the sensory feedback aligns with what the user expects (i.e., the predictions of their internal model). For example, slightly extending the length of the user's arm (figure 3b) or slightly misplacing the user's hand (figure 3c) in VR are illusions that will go unnoticed by users.

Illusions have been explored by researchers to redirect the user's hand while tracing surfaces [1, 20, 42] or reaching [4, 9] to provide an improved perceived haptic sensation and overcome the current limitations of VR technology. In these visuo-haptic illusions the mismatch between the visual and proprioceptive feedback is resolved by visual dominance [15]. Another example of movement-based VR illusions is redirected walking where the rotation of the user's head during turns is remapped to a different rotational angle in VR such that their perceived walking path is altered [35]. In my dissertation, I explore the use of such VR illusions for improving the perceived performance of haptic devices. When utilizing VR illusions, we are concerned with identifying user's perceptual thresholds to ensure that the illusion remains unnoticed. While these illusory interactions are important for improving the perception of realistic VR environments (high degree of verity), prior research has shown that our cognitive system can adjust to repeated exposure to conflicting stimuli [7]; thus, there are opportunities for exploration of overt forms of such remapping techniques that go beyond reality.

2.1.3 Beyond-Real Interactions. For the past few decades, scholars have emphasized the need for further exploration of virtual experiences beyond replication of reality. In 2003, Schneiderman highlighted that there are many opportunities for enhancing 3D interfaces "if designers go beyond the goal of mimicking 3D reality" [33]. In 2005, Casati et al. argued that efforts should be directed towards "creation of virtual perceptual objects that have no equivalent in the hard reality" [8]. Gaggioli suggested, in *Human Computer Confluence*, that "the possible uses of VR range from the simulation of plausible possible worlds and possible selves to the simulation of realities that break the laws of nature and even of logic" and that VR can be used to provide "a subjective window of presence into unactualized but possible worlds" [11]. Bailenson in his recent book, *Experience on Demand*, proposed that the reality bending properties of VR allow us to create experiences "unbound by the law of the real world, to do impossible things in virtual settings" and that "VR is perfect for things you couldn't do in the real world" [5]. Using theories of sensory integration, I study which beyond-real interactions are usable despite the resulting multi-sensory mismatch and utilize sensorimotor control theory to predict learning and adaptation.

3 PART II: VR ILLUSIONS

My research to date has utilized illusory interactions to overcome the current limitations of VR technology by improving the perception of haptic renderings. More specifically, I explored the use of visuo-haptic illusions to improve the perceived performance of encountered-type haptic devices. In the first project, I focused on shape displays, which are matrices of actuated pins that travel vertically to render physical shapes. Affordable shape displays have hardware limitations, such as low speed and resolution. To address these limitations, I employed illusions such as haptic redirection, Control-to-Display (C/D) ratio change, and visual scaling that take advantage of the visual dominance effect, the idea that vision often dominates when senses conflict. The evaluation of these techniques suggested that remapping slanted lines with angles less than 40 degrees onto a horizontal line is an effective anti-aliasing mechanism for increasing the perceived resolution of shape displays. Scaling up the virtual object onto the shape display by a factor less than 1.8x and adjusting the C/D ratio accordingly can also increase the perceived resolution. Finally, using vertical redirection, a perceived 3x speed increase can be achieved [1].

In the second project, I explored the use of quadcopters as hovering encountered-type haptic devices in VR. I presented HoverHaptics, an autonomous safe-to-touch quadcopter and its integration with a virtual shopping experience to demonstrate that quads can facilitate rich haptic interactions by animating passive physical props. The main limitation of quadcopters as haptic devices is their inadequate position control accuracy. To overcome this limitation, I utilized dynamic retargeting, a visuo-haptic illusion that dynamically warps the space based on the position of the quad in real-time, to correct for the offset. This ensures that as the user reaches out to touch a virtual object, their hand is retargeted, such that upon contacting the virtual object, their real hand makes contact with the quadcopter. I concluded by conducting a user study to better understand the subjective user experience when using this dynamic retargeting technique and interacting with a quadcopter in VR [3].

4 PART III: BEYOND BEING REAL

Prior research on sensorimotor manipulation in VR, including my earlier work, has mainly focused on illusory interactions that remain unnoticed by users and has been concerned with detecting these unnoticeable thresholds. Can we go beyond these thresholds and design interactions that embrace the unique possibilities that virtual reality offers? In more recent work, I seek to lay out the design space of VR interactions (more broadly, and not limited to haptic interactions) that go beyond our experience of reality, which I have called “beyond-real interactions”. I explored one such interaction in the context of locomotion in virtual reality, with my mentors at Microsoft Research. We utilized body scale change as a means of increasing the users' perceived walking speed to enable rapid exploration of large virtual environments [2].

I am currently working on building a tool to help researchers and HCI practitioners design effective and usable movement-based VR

Figure 4: Egocentric scale change can enable rapid locomotion through large virtual environments.

interactions. I am drawing on theories from the human sensorimotor system and optimal control to help designers better understand the consequences of their designs. Figure 5 shows control signals within each block in the central nervous system. The feedback controller outputs motor commands based on the discrepancy between the desired and estimated states, which is then combined with the output of an adaptive inverse model [41]. An efferent copy of motor signals is sent to a forward model that predicts the consequences of motor commands [6]. The forward and inverse models are collectively referred to as the internal model [41]. Multisensory integration modifies the original signal based on low-level sensory information, top-down influences of the internal model, and a range of cognitive factors. Prediction errors drive simultaneous perceptual and motor learning [10, 24]. Beyond adaptation to perturbations, humans can learn to synthesize movement under entirely novel dynamics [14]. An example of sensorimotor learning is prism adaptation in which an individual performs perceptual motor tasks while wearing goggles that shift their visual field [28].

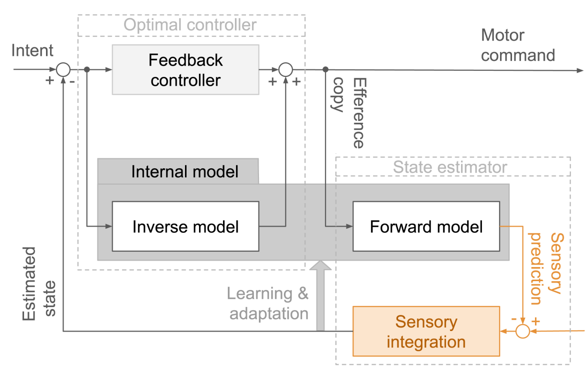

Figure 5: Control signals in the central nervous system.

I hope to use these theories in the design of the tool, to enable researchers answer questions around plausibility [34], usability, aftereffects in long-term use, and individual differences. Designers can define interactions as transformations in the tool, perform one such movement in VR as input, and visualize alternative remappings through simulation. Moreover, they can evaluate their design as it relates to human sensory integration and identify potential sources of sensory conflict. For example, if the tracking data suggests that the user is stationary, but the rendered virtual environment is in motion, designers could visualize this visual-vestibular conflict and anticipate potential vection-induced motion sickness.

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