VR360HD: A VR360° player with enhanced haptic feedback

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Abstract

We present a VR360° video player with haptic feedback playback. The VR360HD application enhances VR viewing experience by triggering customized haptic effects associated with user's activities, biofeedback, network messages and customizable timeline triggers incorporated in the VR media. The app is developed in the Unity3D game engine and tested using a GearVR headset, therefore allowing users to add animations to VR gameplay and to the VR360° streams. A custom haptic plugin allows users to author and associate animated haptic effects to the triggers, and playback these effects on a custom haptic hardware, *the Haptic Chair*. We show that the VR360HD app creates rich tactile effects and can be easily adapted to other media types.

Keywords: Virtual reality; haptic feedback; VR viewing.

Concepts: **• Computing methodologies ~ Virtual reality;** *Human-centered computing ~ Haptic devices;*

1 Introduction

Virtual Reality (VR) has seen a renaissance in recent years – which is attributed to technological advancements in computer graphics and computing platforms, seamless flow of information between hardware and software, and better integration of our bodies, environments and embedded media in an intelligent and meaningful framework. Current VR systems are applied in a variety of user interactions, e.g., watching images, videos and live streams, playing games and augmenting real environments with the digital content. Consequently, a wide variety of 360° media is available for users to entertain and engage in immersive digital environments. Our research is towards enhancing such VR media with coherent haptic feedback, applying an additional layer of sensory feedback to virtual and augmented environments with realistic and causal interactions.

Much of the VR experience couples the audio-visual stream to users' actions and movements. Current VR systems (e.g. HTC Vive, www.htcvive.com; Oculus Rift, www.oculus.com) are paired with hand controllers that not only track users actions, gestures and motion in the environment, but also provide "buzz-like" haptic sensations for reactive feedback. While viewing VR (such as while watching movies, shows and sporting events) a user sits or stands in a relatively restful state and engages with the surrounding VR media. Rather than limiting the haptic feedback to the user's hands, we designed a custom haptic hardware, *the Haptic Chair*, to render dynamic and surrounding haptic effects on the back and the bottom of the user. The Haptic Chair is equipped with two types of vibrotactile (VT) actuators: a grid of VT actuators on the back and a pair of VT shakers on the seat and the back. In this paper, we evaluate the variety of haptic effects rendered on the chair and propose a system to route the flow of haptic media in VR applications.

Current haptic feedback generally consists of simple on/off power modulation with virtually no guiding principles and no predefined rules relating the perceived quality to the quantity of sensations created by the vibrating motors. Recent research has demonstrated building blocks for complex vibratory patterns in terms of physical parameters, i.e., frequency, intensity, location, temporal offset, etc. [BREWSTER and BROWN 2004; MACLEAN and ENRIQUEZ 2003]. More recently, *feel effects* correlated semantic interpretations of events in a story to a parametric composition of sensations [ISRAR et al. 2014]. This allows vibratory patterns to convey meaningful haptic patterns and control a variety of haptic patterns using set parameter values. We apply these feel effects in our framework and create a rich library of haptic effects whose behaviors are tuned by semantic reasoning of normal users.

The organization of this paper is as follows: In Sec. 2 we present a brief background of VR and haptics. This is followed by presentation of the VR360HD framework in Section 3. The design and control of *the Haptic Chair* is presented in Section 4 followed by implementation of the VR360HD in Sec. 5. Finally, we conclude the paper with remarks.

2 Background

Current market trends suggest that pervasive VR is imminent and haptic feedback will be a viable opportunity to enhance users' experience. In this background, we present the current the state of VR and haptic feedback technologies for entertainment and storytelling.

Moving forward with the concept of the "Ultimate Display" [SUTHERLAND 1965], the thrust of current VR advancements is towards reproducing highly immersive visual sensory environments. One common approach uses projected screens surround a user, such as in VR CAVE [CRUZ-NEIRA et al. 1992;]. Another popular approach utilizes head mounted displays [MELZER 1997]. In both cases, user action and behaviors are monitored with sensors mounted in the hardware setup, on the user and/or in the environment. Moreover, sound and haptic feedback are also utilized to enhance the user perception in controlled virtual environments [BEGAULT and TREJO 2001; BURDEA and BROOKS 1996; PAUSCH et al. 1996].

Currently, haptic feedback has been integrated to create comprehensive sensory experiences. Motion platforms and seats are common in VR settings that translate, shake, and tilt the user body in accordance with the dominating visual cues [PAUSCH et al. 1996]. Exoskeletons and grounded force feedback apparatus are used in therapeutic and education settings to render forces against the user's active interactions in virtual environments [BURDEA AND BROOKS 1996]. Other senses, such as those of

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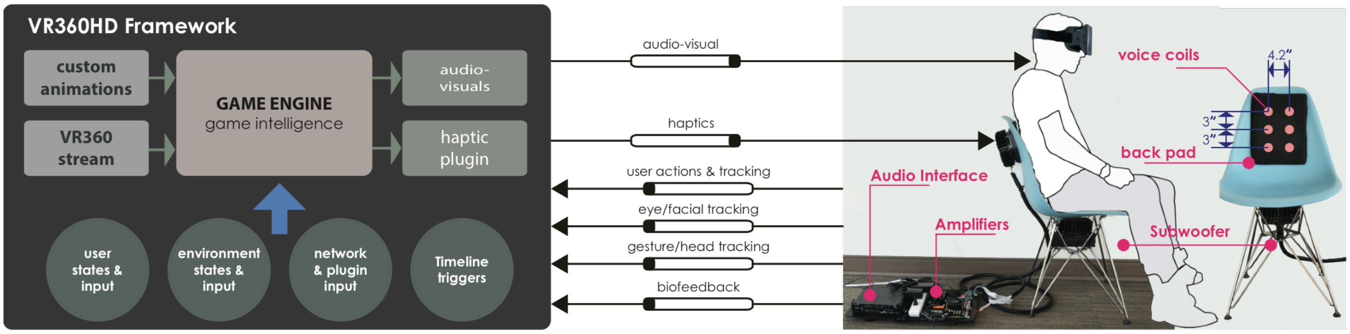

Figure 1: *The framework of VR360HD. The game engine renders animated audio-visual and haptic media defined by triggers and user behaviors and associate them with a VR media stream. Haptics is played back on a passive user sitting on or wearing a haptic device.*

temperature, humidity, air pressure and weak electric shocks also accompany to fill up subtle gaps in immersion [Moon and Kim 2004; Stone 2001]. Current tactile feedback technologies are mechanically driven to create localized haptic sensations all over the body [Lindeman et al. 2006]. The feedback is further enhanced by sensory illusion in tactile perception, such as apparent tactile motion and sensory saltation, therefore allowing sparse actuator grids to render high-resolution haptic effects [Israr and Poupyrev 2011]. Consequently, recent haptic tools allow users to efficiently create dynamic haptic patterns, associate them with the visual-audio media, and render them through multichannel haptic devices [Schneider et al. 2015].

Subsequently, researchers have attempted to develop a haptic vocabulary for neurotypical users that is perceptually differentiable and easily interpreted and learned [Brewster and Brown 2004; MacLean and Enriquez 2003]. More recently, Israr et al. [2014] integrated haptic feedback into a chair to convey the semantics associated with language phrases. They developed *feel effects* that were created using spatially displaced, temporally interspersed pulses. Values for the actuators' parameters (such as the intensity, duration, inter-pulse intervals) were correlated to phrases in the stories, and the parameters were adjusted with the semantic reasoning used in normal users. These feel effects are shown to improve comprehension and memory saliency in 6-8 year old children while reading stories [Yannier et al. 2015]. In this paper, we introduce a set of feel effects and coupled them with events in the VR media.

3 Framework for VR Viewing

In a typical 360° viewing, a user wears a VR head mounted system to experience the world around them by moving their head and body in space. We have classified the VR viewing into two subcategories: i) *active user*: a user actively participates with the 360° media, and ii) *passive user*: a user sits and experiences the 360° content. User activities are limited to head movements, voice commands and minimal hand activities such as, clicking buttons and dialing knobs etc. We propose a framework to account for users' interactions in both VR viewing categories, however in this paper, we only examine a use case for the passive user viewing.

Figure 1 shows the flow of a typical multisensory VR framework. In the heart of it is the VR game engine that collects user and tracking inputs, computes the VR gameplay, and renders feedback to sensory displays. Inputs to the VR engine include: tracking of real and virtual environments; gestures; and body activities (using sensors, IMU, gaze, speech, eye and facial tracking); biofeedback (pulse rate, body temperature, breathing pace, etc.); and messages from other apps, network streams, and software plugins. In addition, a set of triggers can be embedded in the game to initiate other triggers in the gameplay. The VR engine computes the state of the games, executes the game AI (artificial intelligence), and renders sensory output to audio-visual displays.

We have introduced a haptic *playback and authoring* plugin that allows users to create, personalize and associate haptic feedback to the events triggered in the VR game engine. The haptic plugin connects the VR engine to a custom haptic device and allows an authoring interface to render haptic content using audio-based tools. Details about the playback and authoring plugin are presented in the next sections.

3.1 The Haptic Chair: Design and Control

A custom haptic hardware is designed to accommodate VR viewing for a user sitting in a comfortable position. Although our use case enhances the VR movie experience, the apparatus is scalable to playing games, watching sports and other events in social networking. We primarily engaged the back and the seat of a user for haptic stimulations. These body sites cover a significant portion of the human body, usually are not engaged with any activity and provide support to the user. The body sites are ideal for haptic feedback on a resting user whilst sitting on chairs, couches, pads, theater and vehicle seats, etc. A similar setup can be made for love seats, lounge chairs, beds, body vests, jackets and sporting gear. The Haptic Chair is shown in Figure 1. It consists of a total of eight tactile transducers mounted on an Eames® plastic chair. Two inertial shakers (subwoofers) [AST-2B-4, AuraSound Inc.] shake the back and base of the chair. Six vibrotactile actuators [C2, Engineering Acoustics Inc, USA] are arranged in a 3×2 grid, padded into soft foam, wrapped in a cotton cover, and mounted on the back of the chair. The spacing of C2 tactors is shown in Figure 1. The grid pattern is selected to trigger haptic effects at lower-to-mid regions of the user's back.

The eight haptic channels are connected to an audio interface [MOTU, Cambridge MA, USA] that maps them to eight audio channels of a typical computer. Audio channels corresponding to C2 vibrotactile actuators are amplified using 1-Watt audio amplifiers and the shakers are amplified using 100-Watt D-class amplifiers. All transducers have typical controls of frequency, amplitude, modulation, onset and offset of analog/audio waveforms. The vibrotactile grid produces localized moving tactile sensations on the back, and the subwoofers shake two regions on the body, as well as create percepts of moving sensations. In the following subsection, we examine the variability and information capacity of the Haptic Chair. We examine both real and phantom illusions evoked by the chair and explore their control parametric spaces.

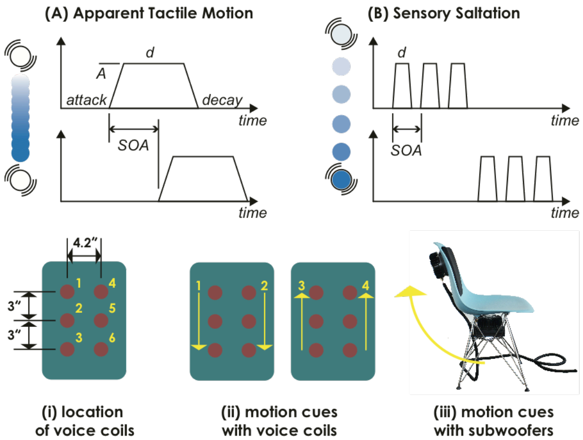

Figure 2. *Variation in tactile patterns examined in studies.*

3.2 Psychophysics of Haptic Effects

Seven participants (5 males, 22-41 years old, average age 26 years) completed three brief experiment blocks separated by small breaks. None of the participants reported sensory impairment to affect the outcome of the experiments and an ethical committee approved the procedures. Participants sat on the Haptic Chair facing a laptop running the experiment protocol, and wore earmuffs to block environmental sound. The experiment session lasted no more than 30 minutes.

3.2.1 Experiment 1: Static Vibration Locations

In the first experiment, identification scores of six locations (Fig. 2(i)) were determined using an Identification paradigm in [TAN et al. 1999]. Each participant was tested for 54 trials with no correct answer feedback. A sinusoidal stimulus of 120 Hz and ~35 dB SL at one of the three randomly selected durations, 150 ms, 300 ms and 450 ms, is presented. The stimulus onsets (and offsets) with a ramp function of 10% of the stimulus duration. Participants felt the stimulus and identified the location by clicking buttons on the computer screen associated with the location of stimulation. Before the main experiment, participants performed a brief familiarity session that played all six stimuli. The experiment block was ~5 minutes. Overall, correct recognition was 81% and estimate of IT was 1.87 bits, meaning that 3 or 4 locations ($2^{1.87} = 3.6$) can be correctly identified by untrained users. Almost all errors were made between adjacent actuators within a column, and left-right distinction was virtually perfect (3 out of 378 trials). The IT rates were 13.19 bits/s for 150 ms, 6.19 bits/s for 300 ms and 3.94 bits/s for 450 ms stimulations.

3.2.2 Experiment 2: Moving Tactile Strokes

Participants identified one of the four motion cues as shown in Figure 2(ii). The motion cues were rendered by sequentially modulating the intensity of transducers in a line with duration *d* that was set as either 150 ms or 450 ms (corresponding to "fast" and "slow" moving strokes). Temporal onsets (*SOA*) between the consecutive transducers were determined by using the model $SOA = 0.32 \times d + 47.3$ [ISRAR and POUPYREV, 2011] (see Figure 5 for timing of stimulation). Stimulus frequency, amplitude and onset functions were the same as in Exp. 1. Participants identified which of the four stimuli (up, down, left and right) was presented in addition to if the motion was "slow" or "fast". Moreover, participants rated the continuity of the stroke in the 1-5 scale (1 being two discrete and 5 means continuous stroke). They became familiar with all eight stimuli in a brief familiarity session. The experiment lasted ~10 minutes. The stimulus-response confusion matrix is shown in Figure 3 (top). Overall, the correct percentage

	SLOW				FAST					Q	
	LD	*RD*	*LU*	*RU*	*LD*	*RD*	*LU*	*RU*		μ	σ
SLOW	**43**	1	1	0	0	0	0	0	left-down	3.3	0.8
	0	**39**	1	1	0	6	0	0	rightt-down	3.4	0.8
	0	0	**35**	1	0	0	1	0	left-up	3.4	0.9
	0	0	1	**39**	0	0	0	**1**	rightt-up	3.4	1.0
FAST	3	0	1	0	**41**	1	1	0	left-down	3.8	0.9
	0	0	0	0	0	**38**	0	0	rightt-down	3.9	1.0
	0	0	1	0	2	0	**35**	0	left-up	4.0	1.0
	0	0	0	0	0	1	2	**54**	rightt-up	4.0	1.0

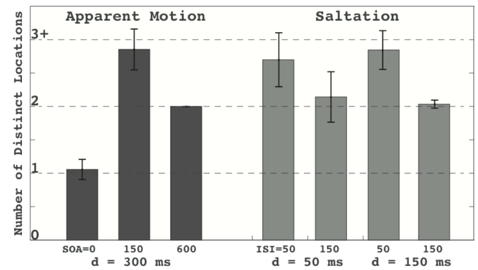

Figure 3. (*Top*) *Stimulus-Response confusion matrix for Exp. 2. (Bottom) Results of Exp 3. Error bars are standard deviation.*

score was 93% and estimated IT was 2.55 bits (*5.9* categories). The identification performance was higher in Exp. 2 than in Exp. 1, indicating better capacity of the back to moving strokes than to static vibrations. Slow and fast distinctions (>95%) as well as up/down and left/right distinctions were high (>97%). Two rightmost columns of Figure 6 (marked under label **Q**) show the mean and std. of subjective ratings of the perceived continuity, indicating higher subjective ratings of fast strokes ($p<0.001$).

3.2.3 Experiment 3: Sensory Illusions with Subwoofers

In Experiment 3, we investigated if tactile illusory motion existed between low-frequency subwoofers stimulated distinct regions on the body (Figure 4(iii)). A low-frequency stimulus (30 Hz carrier with 12 Hz modulation) with intensity of ~30 dB SL is presented on the back and the bottom of the seated participants. To test *apparent tactile motion*, the actuator duration of 300 ms is paired with one of the three SOA levels (0 ms, 150 ms and 600 ms). To test *sensory saltation*, two durations (150 ms and 300 ms) and two ISIs ($= SOA - d$, 50 ms and 150 ms) combinations were tested. Therefore, the stimulus set consisted of 7 vibratory patterns (3 for apparent motion and 4 for saltation). A total of 50 trials were collected per participant. In a trial, a pattern was randomly presented and participants reported the number of distinct *locations of vibration*. Participants reported if they felt "1", "2", or "3 or more" distinct locations. A brief familiarity session was followed by a testing session, lasting ~5 minutes. Figure 3 (bottom) shows average number of distinct locations (y-axis) as a function of the stimulus set (x-axis). For the *apparent tactile motion*, simultaneous actuation (i.e., $SOA = 0$ ms) created a percept of a single location (phantom sensations, [ISRAR and POUPYREV 2011]), and the large temporal separation ($SOA = 600$ ms) was felt as two separate locations. For $SOA = 150$ ms, participants felt illusory motion between the two actuation points. For *sensory saltation*, the illusion persisted for low ISI (50 ms), however, for large ISI (150 ms) the illusion did not elicit robustly. These results are similar to the prior work that showed that sensory saltation existed for small ISIs [CHOLEWIAK and COLLINS 2000], and the moving illusion was evoked at an optimal SOA value [ISRAR and POUPYREV 2011].

4 VR360HD Implementation

The VR360HD application is developed in a Unity3D game engine (Unity Technologies, USA) and tested on a Samsung Gear VR®. An equirectangular video is downloaded from YouTube. A new project is created with build settings for Android (Lollipop) and built-in Unity VR support. The main camera is positioned at the world origin of the scene. A high-poly "Video Sphere", with normal facing inwards, is placed at the origin. The Easy Movie Texture plugin plays the video as a texture on the sphere, and handles playing and pausing the video. The Cinema Suite plugin adds triggers to the video timeline. The UniOSC plugin is used for sending and receiving OSC messages between the game engine and the haptic plugin. The OSC messages are associated with a user's head motion, activities in the videos, timeline triggers and custom functions evoked through other programs. The project is compiled and an executable is stored as an app on the Gear VR's Samsung Galaxy S6 Edge.

The game engine sends OSC network messages to a haptic plugin (Figure 4), which parses them for haptic routing, authoring and playback. Similar to Israr et al. [2014], who coupled Parametric Settings (PS) of a feel effect, such as amplitude, duration, SOA, to Language Phrases (LP) used in stories, we coupled PS to the changes in perceived qualia – as judged by the users. We introduce a library of five feel effects that are used to enhance the sensory experience for VR media. The **Line** effect (Figure 4) is derived from the timing model of tactile apparent motion (Fig. 2) with set parameters of speed (duration, *d*), continuity (*SOA*), direction, location and quality. The **Location** effect plays a list of actuators with sinusoidal waveform for duration *d*. The **Rain** effect plays random actuators with thrust (duration) and tempo (rate) of raindrops. The **Rumble** effect set the waveforms for the two subwoofers. The feel effect **Pulse** associates input from a pulse sensor to haptic patterns. The plugin is developed in Cycling '74 Max (cycling74.com).

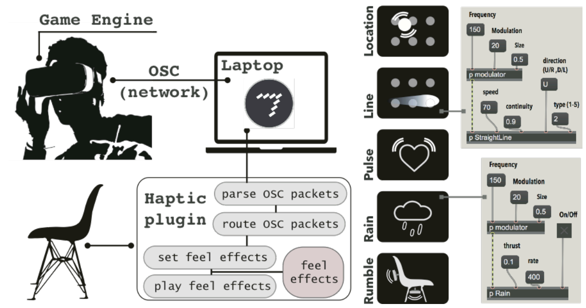

Figure 4. *Flow of haptic media using the haptic plugin.*

5 Concluding Remarks

We present the VR360HD application, a VR video player enhanced with haptic definition. The application plays the VR media on a HMD and triggers haptic messages on user activities and events. The haptic messages are parsed through a haptic plugin that routes the messages to initiate customized haptic effects rendered through a haptic device. In a series of psychophysical studies, we showed that i) the identification performance was better with moving patterns than for static sensations on the back, and ii) the tactile illusory motion existed between two distinct body regions, therefore allowing creation of moving sensory illusions on and around the body. We also presented a library of feel effects that could be used by regular users to enhance VR media with customized and expressive haptic feedback.

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