Evolution from Haptic Feedback Systems to Psuedo Haptic Systems to Enhance Immersion in Virtual Reality

Research Review

Author : Sharathchandra R

Abstract:

The following review explores the various milestones that have been achieved in the development of haptic and tactile feedback systems. It analyses the various practical scalability issues and trade-offs employed in haptic interface design, and investigates into recent trends and developments seen in the evolution of pseudo-haptic systems that enhance user experience in virtual environments. It also expresses the need to integrate the study of vection and self motion enhancement into the field of haptics and finally presents future concerns and possibilities to enrich user experience in critical virtual reality applications.

Introduction:

Haptics is a field of study that explores the complex relationship that exists between the human sense of superficial touch and the virtual world. Haptic interfaces enable human interaction with virtual objects in a computer generated virtual world. This interaction is enhanced by providing haptic force feedback that provides sensory inputs to the user that correlates to events occurring during user manipulation in the virtual environment. As such, though haptics has involved the enhancement of user experience by simulating physical interaction, this definition is now fast blurring with more discoveries and interface desgins being made to exploit other sensory human perceptions that are essential to enhance user experience in virtual worlds. Applications of haptics include tasks pertaining to scientific visualization, interactive 3D product design, robotics, medical applications, simulated specialized training, disability studies & interaction and of course, entertainment applications such as gaming.

Background information and history:

Over the past years, Haptics, as a field of study, has released itself from the confines of robotics to be seen as a vast inter-disciplinary subject that now has a community of its own. Haptics allows direct and immediate control of a user's actions by allowing the user to virtually 'push' and be 'pushed on' by the computer. The feedback systems used to enhance user interaction can broadly be divided into two categories. **Force feedback** consists of devices that interact with the user's muscles and tendons to simulate a feeling of a force being applied. This is achieved by mechanical and robotic actuators that generate physical forces to re-create similar experiences. **Tactile feedback** encompasses the use of devices to induce nervous sensory perceptions of heat, pressure and the feeling of texture. Often used to indicate contact made with a virtual object, tactile feedback is much more complex, as it is bound by research being done in critical fields like neuroscience and other ramifications.

The first demonstrable use and analysis of force feedback systems was proposed and developed by

Maragret Minsky et al.[1995]. Christened the '**Sandpaper'** system, it successfully simulated the feeling of rough textures when a user made contact with virtual 'sandpapers' using a motor-spring driven, 2 degree of freedom (DOF) joystick as an interface. The paper further extends to elaborate on methods to create the illusion of feel and discusses various factors and methods associated with virtual surface and action simulation.

The benefits of using haptic feedback was first seen in teleoperational tasks where the efficiency of the operator showed significant improvement as documented by Massimino and Sheridan [1994]. Similar improvements in user efficiency were observed in the manipulation of virtual objects and critical instruments like surgical apparatus in medical robotics [Semere, Kitagawa and Okamura. 2004]. Limitations encountered in the designing of Haptic feedback systems are partly due to the high cost and lack of transparency associated with building very complex systems with high degrees of freedom and advanced actuators. Simpler devices maybe cheaper and easy to use, although the amount of interaction simulation effects that can be felt are much lesser. Simulation of basic functions such as the prehensile human capability of 'grasping', has yet to reach satisfactory levels.

Sensor-Actuator Asymmetry:

Haptic feedback systems consist of 'sensors' (to sense the suggested apparent motion of the user in the real world) and 'actuators' that provide the actual haptic feedback induced by consequent conditions and states in the virtual world. The number of sensors and actuators determine the quality of interaction to a large extent. As discussed in the previous section, practically scalable haptic feedback systems of the present day contain more sensors than actuators. This results in a 'sensor-actuator' asymmetry. Haptic devices are said to be 'under-actuated' when the number of actuators are lesser than the number of sensors. Although economically more feasible, 'under actuated' haptic interfaces result in a degradation of the perception of effort by the user. For instance, a user might suddenly find himself applying very minimal effort in pushing a boulder.
The effects of Sensor-Actuator asymmetries were studied by researchers at Stanford, **[Barbagli and Salisbury,2003]** and have some interesting results.

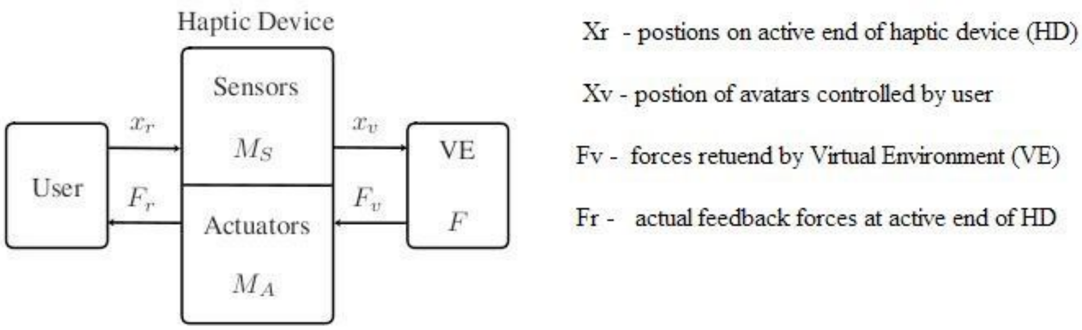

Fig. 1 : Possible structure for a haptic feedback interface [Bargbali and Salisbury, 2003]

Bargbali and Salisbury used terms from control theory to loosely relate the haptic interface design to the more formal definition of 'controllability' and 'observability'. Controllability (defined as the ratio k= number of sensors (s)/ (n) number of variables needed to describe an avatar position) represents the ability of the user to control movement of the avatar in the virtual environment. If k=0 (no sensors), the user has no control as opposed to full control at k=1. Observability (o), similarly represents the capacity of the VE to exert feedback along certain dimensions on the user (o
= number of actuators (r)/ (n)) and if o = zero, the user perceives no feedback and o=1 if maximum feedback is perceived.

Bargbali and Salisbury recreated a 'pinch grasp' that uses both hands to grasp a virtual object. This

is an action that can be fully described using 6 variables, and hence needs 6 sensors and 6 actuators to achieve perfect realism. However only one motor was added to an existing state of the art 3-Degree of Freedom (DOF) device. Though a 4 DOF actuator device did not provide perfect realism,it was simpler, cheaper and more transparent. The device was based on a PHANTOM 1.5 with a force reflecting gripper connected to a sensorized wrist, and thus had a sensor with 6 degrees of freedom, that allowed the virtual object to be pinched using the index finger and thumb. Perfect controllabilty is achieved, but observability is limited in this asymmetric device ($o < k = 1$).
Unrealistic experiences (overly active or passive responses) were displayed along the line of action of the force-reflecting gripper that represented projection of torques.

It was deduced that although 'under-actuated' devices maybe cost-effective and more transparent and that adding more sensors than actuators might increase usability, the systemic forces however tend to become non-conservative, leading to a loss of realism. High asymmetry is certainly not feasible in critical virtual environments (like space robotics or medicine) where a high level of realism is mandatory.

This paved the way for the creation of several haptic rendering techniques for asymmetric interfaces in order to mitigate such unrealistic effects. Several methods of 'pseudo haptic' feedback have been suggested in the past. **[Massimino and Sheridan]** have proposed substituting missing haptic information of contact force using a modulated auditory feedback. **[Koutek and Post]** used spring based tools to manipulate virtual objects. We shall now examine the most recent pseudo haptic interface using visual feedback to create 'haptic illusions' as suggested by Lecuyer et al [2005].

The A_4 Technique to Improve Perception of Contacts with Under-Actuated Devices in Virtual Reality[Lecuyer, et al.]:

The proposed A_4 scheme, Automatic Alignment with the Actuated Axes of a haptic device involves moving the virtual scene to provide a visual effect that enhances the sensation of 'contact' in an under-actuated haptic interface. The proposed method restricts itself to point based interaction commonly found in haptic interface based softwares that deal with paintings, sculptures and 3D product design. It is also focusses only on Cartesian haptic devices, in which sensors and actuators are aligned with the axes of the orthogonal frame. **The figures below, were obtained from the paper describing the A_4 technique by Lecuyer, et al [2005]**

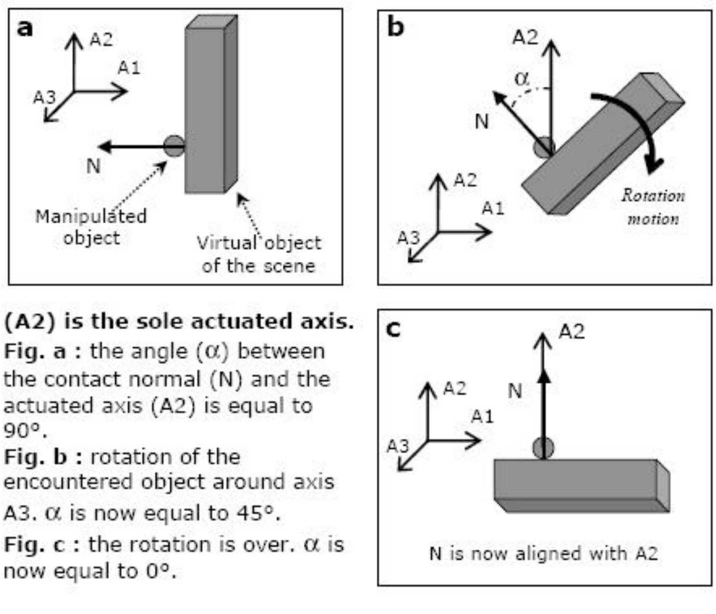

Fig 2 : Concept of the A_4 technique [Lecuyer et al, 2005]

In this method,only one point on the 2D horizontal plane is modified by the user. The actuated axis of the haptic device is restricted to axis A2 and A1 is not actuated. Therefore, in the under-actuated haptic feedback device, only one component of the actuating feedback force along one direction of the horizontal plane was perceived while the other component was set to zero. When the manipulated object is moved to make contact with the virtual object in the scene, the Normal at the surface of the virtual object is not aligned with the actuated axis A2. The virtual scene is rotated along axis A3 to facilitate this alignment of the actuated axis with the normal. The perceived visual effect is intended to enhance the feeling of making contact using an under actuated device.

The figure below shows the step-wise implementation of the technique that begins with measuring the input motion of the device along three Cartesian axes and applying motion to the manipulated object using the 'camera metaphor' so that the manipulated object is always at the centre of the screen. This is followed by collision detection to determine if the manipulated object has made contact with any virtual object in the virtual environment and if so, the normal at the point of contact is made to align with the actuated axis by rotating the virtual scene.

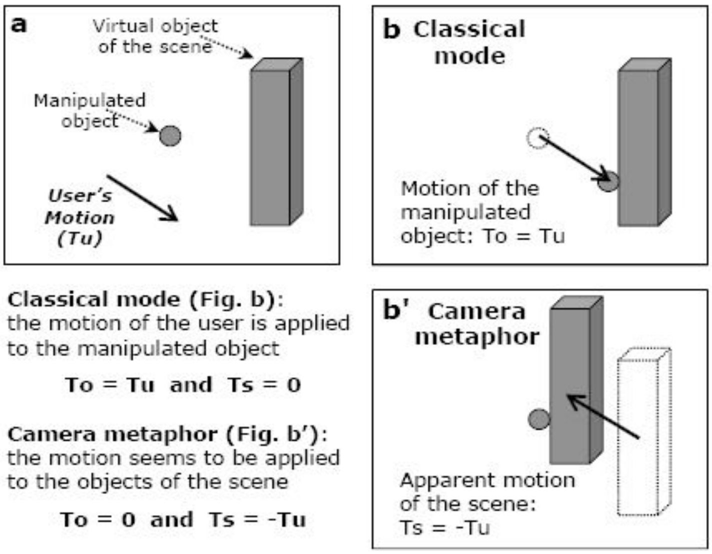

Fig 3 – Use of the 'camera metaphor' during rotation of virtual scene (Obtained from paper by Lecuyer et al [2005])

The above method was tested on users in experiments carried out in conditions of full haptic feedback, under-actuated haptic feedback and in the absence of haptic feedback, alternately disabling the rotation of the virtual scene in some cases and the results were quite revealing. Although under-actuated feedback resulted in sudden attraction or repulsion towards the user (which was absent in fully actuated conditions), there was a definite benefit when compared to conditions of 'no haptic feedback' as the users felt more guided at the surface of the virtual object. Although the subjective perception of making 'contact' improved by using the A_4 technique, the rotation of scene sometimes impaired the user's task of moving along the contour of the surface of the virtual object when it was constantly moving.

Therefore it is deduced that if the designer wants to focus on user performance, the A_4 technique may be discarded. However if the focus of design, centres around haptic perception of the user, then the A_4 technique is extremely suitable.

Perception of Psuedo-Haptic Textures (Perceiving Bumps and Holes without a Haptic Interface) [Lecuyer et al 2004]:

The use of efficient haptic force feedback or tactile feedback interfaces are confronted by many limitations of cost, transparency and usability. Several proposals have been made in the past to simulate haptic sensations without the use of haptic interfaces. For instance, sensory substitution has been used for space gloves and space robots by [**Crabb et al, 1987**]. Pseudo Haptic feedback initially developed by using visual feedback along with a normal input device.

The use of Pseudo-Haptic textures to simulate bumps and holes in surfaces **[Lecuyer et al 2004]** is inspired and based on analogous designs in the domain of haptic feedback systems.

- As mentioned earlier, seminal work associated with the simulation of bumps on a rough texture using force feedback was done by Margaret Minsky [1995] (The Sandpaper system). The force feedback in the 'Sandpaper system' was greater when the bumps were steeply sloped giving the user the impression of moving a stylus on a rough surface.
- Recent research by Hayward et al [2001], showed that during conditions of perceptual conflict between vertical motion and the lateral force information, subjects globally refer to the lateral force information to perceive bumps and holes.
- Many algorithms that simulate textures with force feedback are based on 'Bump Mapping', a concept widely used in computer graphics to create the appearance of rough surfaces by perturbing their normals.
- Psuedo Haptic concepts were used to simulate conditions like friction and stiffness between virtual objects. For instance, while simulating friction caused due to inserting one object into a slightly narrow opening, the speed of the virtual object being inserted is decreased. This results in the user increasing the pressure on an input applied to the device, which effectively simulates the condition of friction.

Based on the above listed concepts and practices, the pseudo-haptic method proposed by Lecuyer et al. to perceive bumps and holes is fairly intuitive:

The method basically consists of modifying the motion of the cursor as it passes over a texture which resembles a bump or a hole. The control/display (C/D) ratio is varied as a function of the "height" of the terrain of the surface of the virtual object over which the cursor is travelling. In other words, a deceleration (negative acceleration) of the cursor indicates that it is travelling over an up-slope of a bump, and an acceleration of the cursor indicates that it is over the downward sloping region of the bump. For a hole, the upward sloping condition(deceleration) refers to exiting a hole, which is preceded by the intial acceleration.

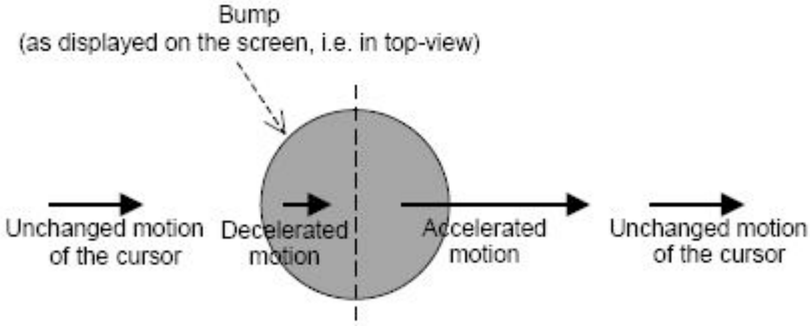

Fig 4 – Modification of the speed of a cursor when passing over a bump.
(Figure obtained from the paper of Lecuyer et al [2004])

The algorithm works on a pixel by pixel basis of varying the C/D ratio, assuming that information regarding the height map (distribution of heights for pixels on the screen) is known. As the input device is moved, the 'cost of displacement' along the path is computed. If the displacement between consecutive pixels is greater than one, it denotes ascension and a negative displacement denotes a downward slope. Mostly all irregularities can be mapped onto three well know mathematical profiles-- a gaussian profile (resembles a bell curve), a polynomial profile and a linear profile.

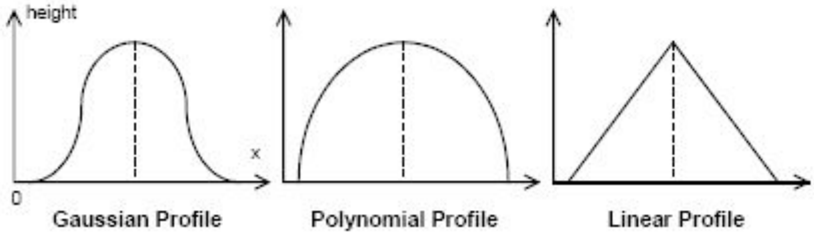

Fig 5. Profiles used for simulation of bumps

For simulation of holes, the height of the above profiles and hence height associated with each pixel displacements become 'negative'.

The results of testing the above pseudo-haptic texture scheme on users revealed that users were able to visualize the shape and topography of the bump or hole, and almost often their mental image matched the simulation profile used in the virtual model. The proposed applications of this method include feeling of images and pictures, geographical information systems , visualization of scientific data and perception of GUI components like edges and raised 'buttons'.

Enchancing Self Motion Perception (Vection) in Virtual Reality:

The principle role of haptic force feedback has so far been restricted to the simulation and enhancement of physical perceptions associated with modifying virtual objects. However, when it comes to vection and self motion perception, the simulation takes on more of a neurological aspect. Affordable and effective motion simulation still remains a challenge. Although the topic of 'vection' might seem out of the scope of typical haptics, it calls for essential consideration on part of researchers wishing to achieve realism in interactive virtual environments as answers to most unsolved problems in this domain lie in further investigation into the allied fields of psychophysics. In fact, frequent disorientation is experienced during navigation of virtual environments when self-motion is directed by solely visual cues.

User generated motion cueing [Riecke, 2006]:

The research by **Bernhard Riecke [2006]**, explores the possibility of user-generated motion cueing to enhance self-motion perception in virtual reality by the use of a translational and rotational motions produced in a wheel chair. When compared to previously existing methods to induce vection like treadmills and motion platforms, the proposed approach of Riecke has minimal requirements in terms of costs, required space, safety features and technical expertise.

Related work and issues in Vection systems:

One of the most frequently quoted examples of self-motion perception is the 'train illusion', where a person seated in a stationary train suddenly feels like he is moving when another train in an adjacent track chugs along slowly. In the laboratory, a commonly used apparatus to study vection is the optokinetic drum (a large rotating drum painted with black and white stripes or dots). Although the realization of self-motion is instantaneous in the 'train illusion', in the lab setting of simulated virtual worlds, vection occurs only after an onset latency of 2-30 seconds. **Vection onset time** is often a yardstick used to measure the effectiveness of a simulation design in inducing a sense of self-motion in the user.

Wong and Frost [1981], studied the onset time for visually induced circular vection (self- rotational illusion) can be reduced by simultaneous rotations with 30^o max deflection, with peak accelerations of $240\ ^o/sec^2$ occuring in a motion duration of 1.1s). These were recently converted to translation vection values by Riecke et al [2005] figuring to small physical jerks (displacements) of 1cm and $0.8m/sec^2$ or 3cm and $1.6m/sec^2$, which not only decreased vection time but increased the effectiveness of illusion of vection.

The set-up for the user-generated motion cueing system proposed by Riecke consisted of a standard manual wheel chair with elastic bands attached to the wheel, to provide automatic re-centering similar to that seen in joysticks. Thus the motion of the wheelchair was restricted to +/- 8cm for translatory motion and +/- 10^o for rotations. Potentiometers were used to measure the wheels motion and the wheelchair interface was USB enabled. The translational/rotational velocity of the virtual scene was mapped onto the translationa/rotational deflection of the wheelchair.

Fig 6. Pictures of the user seated in front of the cylindrical projection screen on the modified wheelchair used in the velocity controlled motion model, where minimal motion cueing is provided by the user themselves.

When compared to vection induced by button-based and joystick based systems, the wheelchair showed lowest vection onset latencies and was rated highest for convincingness and intensity of perceived self-motion. Vection onset times was halved and intensity of vection doubled, for linear translation.

This is the first case where a user-generated cue to enhance vection was proposed. The wheelchair interface is compact, cost effective, easy to use and requires minimum safety precautions and programming efforts. Moreover it is an ecologically plausible locomotion metaphor that can be used for a large number of VR applications. Further research to improve the efficiency of such self-generated motion cueing is awaited.

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