Scaled Haptic Props for VR - Literature Review

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ABSTRACT

The goal of virtual reality is to create immersive and realistic simulation. A key part of creating this is giving believable haptic feedback, the feedback received by a user's sense of touch. This literature review aims to look at how humans perceive handheld objects and the types of haptic feedback that can be generated, along with their impact on enjoyment and performance. The focus will be on low cost passive haptic props along with dynamic passive haptic feedback. This shows the viability of simple weighted props and the effectiveness of manipulating the weight properties of a prop to make it appear larger than it actually is. A weighted prop that is able to dynamically change its static moment is shown to be able to represent multiple different props and leads to greater immersion and performance.

CCS CONCEPTS

• **Computing methodologies** → **Virtual reality**; **Perception**.

KEYWORDS

Haptic Shape Perception, Dynamic Passive Haptic Feedback, Virtual Reality, VR Props

1 INTRODUCTION

Virtual reality has progressed extremely quickly over the last few years, with immersive VR headsets such as the HTC Vive, Oculus Rift and PS VR being available to the general consumer for home use. One aspect often overlooked is the design of the controllers used and the feedback they provide. Controllers being the handheld input devices that allow the user to interact with the game world. One aspect often overlooked is the design of the controllers used and the feedback they provide. The controllers often have simple triggers to close or open fingers and at most provide vibrational feedback to the user. Whether interacting with a heavy, light, big or small object the haptic experience of the user is identical. No matter how good the visual and audio simulation there will still be a divide in what they are seeing in the virtual world and the feedback they are receiving from their hands. The field of haptic feedback looks to create devices that try and match real world interactions by providing a sense of weight, texture and resistance. Haptic devices try create a greater sense of immersion for the player. This also has the bonus effect of better performance by the user, since they feel more comfortable within the virtual world and are able to approach challenges in a natural way. This paper will look at the history of haptic feedback, starting with the pre-VR concept of Dynamic Touch. It will then explore the different types of feedback, namely active and passive, and will then look at the experimental use of feedback in haptic retargeting and reconfiguration. The main focus will be on passive rather than active feedback with particular focus paid to the new field of dynamic passive haptic props.

2 DYNAMIC TOUCH

Dynamic touch is an area of study that predates VR. It was first described by Gibson[15] in 1966. It refers to the ability of people to perceive the weight and height of an object just by holding it, even if the object is not visible. In experiments by Turvey & Burton et al.[23] it was shown that there exists a "rudimentary capability of nonvisible shape perception". This ability to perceive an object's properties is most influenced by the objects inertial properties. Kingma et al.[17] explored the impact of these inertial properties and proposed that the single most important factor in an object's perceived weight and height is the object's *static moment*, the mass times the distance between the point of rotation and the centre of mass. The importance of an objects *static moment* has also been demonstrated by Burton et al. and Pagano et al.[6, 20]

More simply put, in a handheld object the further the object's center of mass is from the user's wrist the heavier and longer the object is perceived to be. This phenomenon is extremely useful in the design of VR props since a small prop can be perceived to be a different shape/weight by manipulating the prop's *static moment*.

Weighted props are not a new concept in VR for instance, Fujinawa et al.[12] were able to build a *shape perception model*. This provided a "mapping from the mass properties of the controller to its perceived shape" To build this they presented users with a number of 3D printed props with weights distributed to give them each unique mass properties. The user only saw a virtual representation of the object and was able to change the virtual object's height and width until they believed it matched the held object. Testing showed that users perceived the intended shapes irrespective of the controller's actual appearance. For instance a tennis racket prop was designed that was half the length of an actual racket but was still perceived as normal sized due to the prop's weight distribution.

3 HAPTIC FEEDBACK

Haptic feedback is commonly classified into two types, **passive feedback** and **active feedback** [3, 16, 25] these two categories can also be further subdivided.

Passive Feedback

Passive feedback can be divided into **passive tactile** and **passive kinesthetic**, where the former is the sensation of shape and texture, while the latter is the feedback given by the weight. Kinesthetic feedback can be manipulated using the object's static moment as shown above.

Passive haptic feedback creates immersion since the user is able to match what they are seeing to what they are feeling. When they touch or pick up an object in the game world, a passive haptic prop is able to provide a sensation of shape, texture and weight. This was well documented by White[25], showing that both a solely tactile and a tactile weighted baseball bat prop led to greater immersion and performance in a simulated baseball game than traditional VR controllers. When using a VR controller, only 58% of users adopted a traditional side-on batting stance, the rest simply standing front on and swinging with one hand. Given a tracked bat handle that could provide realistic tactile feedback the adoption of a two-handed side-on stance rose to almost 100%. This tactile feedback led to a noticeable increase in game immersion. This was further increased by adding lead weights to the prop to provide more kinesthetic feedback. The additional kinesthetic feedback also led to better performance with an increase in user's hit/miss ratio and average distance per hit, with user's hitting 24% further. When the batting experience was made more realistic by including a haptic prop, the user experienced greater immersion and performed better.

Active Feedback

Active Feedback can also be divided into **active tactile** and **active force-reflecting**. Active tactile is a response meant to emulate an impact without actually restricting movement, usually in the form of a rumble response. This is the form of haptic feedback most people are familiar with, being present in mainstream consoles since the N64 with their "Rumble Pak"[11]. Rumble responses have been used historically in video games to indicate specific interactions (taking damage, colliding with an object etc.) but have also helped build narrative and immersion[26]. Active tactile feedback is also present in modern day touchscreens to provide a haptic response to button presses [13]. This is required since there is no feedback from a key press or button click so without the vibration the user has no haptic way of knowing if the input went through.

Force-reflecting provides actual resistance to movement. They often through the use of an exoskelton device which is fitted onto the user and using motors, actively resists the users movements. This form of feedback is highly immersive as the user receives actual resistance to movement and the device can simulate external forces. These devices are usually highly technical, experimental and expensive putting them out of reach of almost all consumers. Active Force-reflection, especially from a user mounted device, is largely beyond the scope of this paper but there are numerous interesting implementations of the concept [1, 4, 10, 21]

4 HAPTIC RETARGETING

One of the problems with passive haptics is that a controller/prop can only have one shape, so can only represent one thing. The object also can only exist in one place at a time so the cannot be interacted with in different places without moving the prop. Haptic retargeting is a strategy to try overcome this. There is a certain amount of sensory conflict the human perceptual system is able to tolerate. What a person sees does not have to exactly match where they believe their hands should be, there can be a mismatch[5]. In these situations there is what is known as visual dominance, where your visual perception wins out in the case of these sensory conflicts[14]. A person's brain chooses to believe the visual information it is receiving rather than their other sensory information, this can be leveraged by VR. The virtual space can be subtly warped in order to trick the user into interacting with a specific object or part of an object and believe that it is a new object or in a different place.

Kolhi et al.[18] showed how a multi-directional tapping task can be performed in VR even when the virtual and real world board are orientated at a different angles. Users were told to interact with a board that, without their knowledge, was tilted so it did not match the orientation they saw in the virtual world. Within a certain range of orientation there was very little difference in the performance of the users when interacting with a tilted board. They also explored the the detectability of the retargeting and found that a difference in orientation of +/-12 degrees was not easily detectable by users. However after that threshold it quickly became extremely detectable, suggesting that 12 degrees was the limit of visual dominance.

Azmandian et al.[3] tricked users into believing they were stacking three separate cubes but were actually interacting with the same cube each time. This was done by distorting the impact of user's movements in the game world through a process they called body and world warping, as well as a hybrid of the two. In body warping the virtual hand of the user is translated in various directions incrementally as the user moves until they have been re-targeted. World warping involves scaling a users head movements so that they have a reduced/increased effect on the game world without the user noticing. Users were able to successfully stack the virtual cubes without noticing the body and world warping. The paper also found that there were limits to the amount of warping that could be done without the user noticing. Warping had to be done incrementally, so worked better with slow long movements. If users moved quickly there was very little time for warping to be applied. Instantaneous warping was highly noticeable and broke immersion. World warping had to be masked by the user's head movements so could not be applied if the user looked away from the object or did not move their head.

This was expanded upon by Chenh et al. [8] who created a curved dish with 25 panels at different angles which they called a *Sparse Haptic Proxy*. When the user reached out to touch a virtual object they were redirected to touch a particular part of the dish. They used three different methods of retargeting, one that only resulted in back and forth redirection. One that just moved the user to the nearest point to minimize the amount of warping and finally one that heavily redirected the user so that the surface angle most closely matched the virtual object's angle. Participants ranked minimal movement and only back & forth retargeting equally but none preferred the third heavily redirected approach. This shows that while this on-the-fly target remapping was able to add to the user experience, if overdone, it becomes undesirable.

Haptic retargeting is shown to be a viable way to provide passive haptic feedback while reducing the number of required props. There is however a limit that the human brain will accept before it is noticeable and thereafter has a negative effect on user experience. It also becomes less effective when the user makes small or fast movements as retargeting cannot be subtly applied.

5 HAPTIC RECONFIGURATION

Rather than retarget the user's movements, another strategy is to change the real world environment in a process known as **haptic reconfiguration**. Since the user cannot see the environment they are in, it can be manipulated in order to provide a dynamic virtual experience.

Snake Charmer [2] uses what they call an *encountered-type haptic interface* which utilizes a robotic arm. The robotic arm can attach to a number of endpoints. These endpoints were split into passive, input and active. Passive endpoints provided different shapes and textures for the user to interact with. Input endpoints were various sensors or buttons a user could press. Active endpoints included a fan and a heating/cooling element to simulate air flow and temperature. When a user reached out to touch something the robotic arm attached to the appropriate endpoint and positioned itself to meet the user's hand. In this way multiple props can be realistically simulated without the user having to consciously position or swap between them. While the arm can quickly position itself it still has a limited range. Interactions were only available within range of the arm, which was a 0.54m x 0.51m x 0.44m space. While users were able to grab and move the object within this range it is still a limited window in what is supposed to be a complete 3D virtual world. Swapping between endpoints also takes time so it was not feasible if the user wished to interact with different objects quickly one after another.

Vonach et al.[24] had a similar implementation with a robotic arm that was able to hold up a surface to meet a user's hand and provide feedback. It addressed the limited interaction space by placing the user on a omni-directional treadmill where the user could walk around but remained in the same place. They also theorized how 3 separate robotic arms would be able to provide 360 degrees of coverage. This does however mean that implementing this would require highly technical and expensive robotic arms.

Both of these reconfiguration solutions require expensive robotic equipment and struggle to provide feedback if the user moves too fast or swaps between interactions too quickly.

TurkDeck[9] provided a non-robotic solution and used actual humans to move props and construct environments. While the user was in the virtual world, a team placed objects around the user to create corridors, ledges, balancing beams and a table & chair. While obviously having a team to construct environments is not feasible to most users, *TurkDeck* did demonstrate how a small number of props can be reused to create a highly immersive environment at a low-cost.

Cheng et al. then iterated on *TurkDeck* to create *iTurk*[7] which used similar low cost multi-purpose props. Instead of having a team or robot creating the environments *iTurk* integrates the reconfiguration of props within the game experience. A user is prompted to interact with a prop in a certain way and unknowingly sets the prop up so that it could be reused later. In one example a ball was suspended in front of the user, the user was prompted to hit the ball setting it in motion. The swinging ball was then tracked and the user was presented with various enemies to hit, each one corresponding to the current position of the ball. In this way a single prop could be interacted with multiple times in multiple different locations without the need for a robotic or human assistant. This does mean however that the game world interactions have to be tied to what is happening in the real world. Therefore what can happen in the virtual world is very limited and if the user does not correctly set up props they are thereafter rendered useless.

Haptic reconfiguration can be effective but does mean that the virtual world is limited to what can be setup in the physical world and as shown often requires expensive equipment. However *TurkDeck* and *iTurk* did show it was possible to create effective low-cost multipurpose props.

6 DYNAMIC PASSIVE HAPTIC FEEDBACK

While passive weighted props are effective at performance and immersion [25] their main issue lies in their lack of generality. While retargeting and reconfiguration attempt to address this they have many noticeable limitations. Zenner and Kruger [27] introduced an alternative with the concept of Dynamic Passive Haptic Feedback (DPHF), where a single weight-shifting prop could take the place of multiple props. DPHF does not require any robotic arms or complex warping but rather uses simple motors to alter the shape and weight properties of an object.

Shifty

Shifty was the first DPHF prop designed by Zenner and Kruger [27]. The prop consisted of a VR tracked lightweight rod with an internal lead filled weight. This weight could then be moved up and down the rod along a belt using a stepper motor which could receive commands from the game world. The shifting weight caused a change in the static moment of the object leading the object to feel heavier or longer in the users hands.

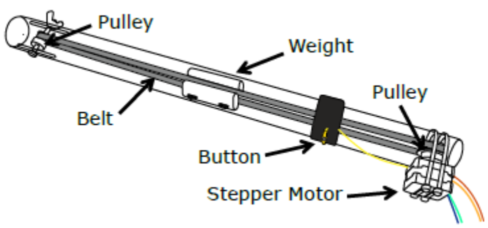

Figure 1: Concept sketch of *Shifty*, Zenner and Kruger[27]

Shifty was used to simulate a telescope where users could extend the telescope to change it's length and thickness in the virtual world. As the telescope was adjusted virtually the internal weight of the prop moved to try and accurately represent the new static moment. Users reported a very strong feeling that the real world prop was actually getting longer and thicker despite there only being internal weight movement. In a second experiment users were asked to use the prop to pick up a light, medium and heavy cube. The goal was to try simulate the instantaneous change in weight when picking up a object. Since the internal weight took time to move to the correct position there was a mismatch between the expected instantaneous weight and the actual transition. To overcome this various different *loading* animations were added. The most successful being that the picked up object started small and scaled up to the correct size. *Shifty* performed twice as well as a passive prop in terms of perceived realism and fun experienced by the user. *Shifty* may have performed better with a internal weight that could move faster between states to better simulate an instantaneous change in weight, however users did report being able to feel the vibrations of the motor and that could provide unwanted feedback. Both experiments were however only performed on a small sample size (n=12).

Drag:on

Drag:on is another DPHF prop by Zenner and Kruger[28] and was centered around using air resistance to provide different amounts of passive haptic feedback. The device consisted of a handle with two folding fans on either side. The fans could each open independently to create a variety of different props, each one with a different amount of drag. When the prop was swung through the air the varying amounts of drag made the prop feel heavier and simulated resistance.

Figure 2: *Drag:on* in one of its possible states, Zenner and Kruger[28]

The resistance provided by the prop was not in a constant 1-1 manner but rather varied with the velocity and force provided by the user. This could be used as a crude but low cost alternative to active force feedback and provided resistance in a way that a simple weighted prop was unable to. Zenner and Kruger presented users with various different scenarios where they were able to interact with objects presented as light, medium and heavy. In one example they were asked to move wagons that were empty, half-full and filled. What they found was that *Drag:on* was very successful in creating a perceived range of resistance. Users really did feel like the objects presented as heavier did in fact feel heavier because of the added resistance from the prop. However, if the user orientated the fans parallel to the direction of movement then there was very little resistance. If the fan is orientated incorrectly it does not provide feedback. Additionally if the prop was stationary it provided the same amount of kinesthetic feedback regardless of fan state. In order to make a haptic impression the controller needed to be moved. So while it can provide quality feedback while in motion, it was ill suited for stationary tasks such as just holding a heavy virtual object.

ShapeSense

Liu et al.[19] took the weight shifting idea from *Shifty* and added the benefits of air resistance given by *Drag:on* in a prop they called *ShapeSense*. The prop was made up of three shifting panels/sails that could move up and down a held handle. Each panel could also overlap reducing the overall air resistance of the prop. The prop could dynamically create different amounts of drag but also change the static moment and perceived weight of the prop by moving the panels further away from the user.

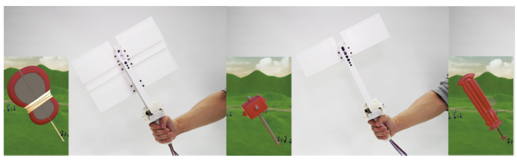

Figure 3: *ShapeSense* in two of its possible states, Liu et al.[19]

ShapeSense has had minimal testing but used 210 sets of data to help form a perception model similar to that developed by Fujinawa et al.[12]. They were able to find the possible area that could be rendered by *ShapeSense*. While being able to provide dynamic passive feedback when held due to its shifting weight it still ran into the same problems found in *Drag:on*. If swung at the incorrect orientation or held stationary it provided no haptic impression.

Transcalibur

Transcalibur by Shigeyama et al.[22] used a similar idea to *Shifty* with a 3D printed weight moving up and down an arm. However Transcalibur improved on this design by having two of these arms. Additionally each arm is attached to an angular mechanism that can rotate up to 90 degrees. In this way each weight can be placed anywhere within a quarter circle. This advanced weight placement allows for a variety of props including those with symmetric and asymmetric shapes. *Transcalibur* was used to represent a sword, a gun and a crossbow just by re-positioning its weights.

Figure 4: *Transcalibur* representing three different possible props, Shigeyama et al.[22]

When rated on a 7-point scale, 197 users answered that the device made them actually feel change in width(6.0) and height(5.8). When using the device immersion and realism were also highly scored (6.2 and 6.0). However this was not tested against a static passive prop or a standard controller. The paper also did not investigate the effect that transition time played in the shape perception. Similarly to *Shifty* the device took time to transition between states so could not effectively provide instantaneous sensations of weight. The testing was only focused on 2D shape rendering so it is unknown how well the object would be able to render complex 3D shapes. A further project could give the arms three degrees of movement rather than the two currently implemented. It could also be tested more vigorously against non-moving passive props and standard controllers.

7 DISCUSSION

Clearly there exist multiple very different strategies when it comes to implementing haptics within VR. **Table** 1 below compares each method for generating feedback. Every method examined did provide some benefit to user's performance or immersion, showing that haptic props should always be implemented when possible. What becomes apparent is that the most impactful solutions are also the most expensive. Solutions that provide actual resistance require complex robotics. Using air resistance can somewhat address this but only if the prop is moved in the correct orientation. Haptic Retargeting and Reconfiguration were shown to be effective but imposed many limitations on what is able to be simulated and what the user would be able to do within the game world. Decreasing these limitations came at a sharp increase in cost and complexity. A low-cost yet widely applicable solution using these methods does not currently exist. Passive tactile, kinesthetic and active tactile can all be used together. DPHF takes all the benefits of passive feedback but also addresses some of its weakness. The only drawback being that dynamic solutions are more technologically complex to implement. It is still unknown how effectively DPHF is able to simulate 3D objects and there may be more effective ways of shifting the static moment that have not yet been explored.

Table 1: Haptic Feedback Comparisons

Method	Impact Potential	Cost	Technical Complexity	Range of Applicability
Passive Tactile	Limited improvement	Low-cost	Low-tech	Single use per prop but wide overall range
Passive Kinesthetic	Allows props to be perceived larger than they are	Low-cost	Low-tech	Single use per prop but applicable in all props.
Active Force	Extremely high level of simulation provided	Very expensive	Very technically complex	Currently not viable for main stream usage due to cost
Active Tactile	Low Impact on performance and immersion	Low-cost	Low-tech	Integrates well with other forms of feedback
Haptic Retargeting	Effective at tricking users within a certain range before becoming noticeable	Very little additional equipment required	Intensive warping and retargeting software required	Not suitable for fast or small movements
Haptic Reconfiguration	High level of impact possible with only a few props	Requires an expensive robotic arm or someone to move props	Robotic solutions technically complex	Struggles with interactions in quick succession and virtual world dependant on real world.
DPHF	Allows one prop to realistically represent many different ones	Requires only basic motors and electronics	Moderate complexity	Wide range available to single device

8 CONCLUSION

Currently it is proven that weight plays a large role in the perception of an object and in-game immersion. Passive props are an effective way to effect immersion and do have a proven positive effect on performance. Many other options exist to provide haptic feedback but they are often limited in application, highly complex, very expensive or a combination of the three. There is room for the exploration of simulating multiple props with one shifting dynamic prop, especially for 3D shapes since current research has focused on 2D shape rendering. Dynamic shifting props may also be able to simulate instantaneous weight and resistance but further study is required.

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