Preliminary Study on the Use of Off-the-Shelf VR Controllers for Vibrotactile Differentiation of Levels of Roughness on Meshes

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Abstract: With the introduction of new specialized hardware, Virtual Reality (VR) has gained more and more popularity in recent years. VR is particularly immersive if suitable auditory and haptic feedback is provided to users. Many proposed forms of haptic feedback require custom hardware components that are often bulky, costly, and/or require lengthy setup times. We explored the possibility of using the built-in vibrotactile feedback of HTC Vive controllers to simulate the sensation of interacting with surfaces with varying degrees of roughness. We conducted initial testing on the proposed system, which shows promising results as users could accurately and within short time discern the amount of roughness of 3D models based on the vibrotactile feedback alone.

1 INTRODUCTION

In recent years there has been a steady rise of the number and quality of VR solutions. All these systems aim to immerse users by using a combination of visual and audio modalities together with a sense of presence in the VR environment, which is achieved by internal or external head and hand tracking. For interacting with the VR environment, the state-of-the-art solutions usually rely on controllers. However, the reliance on controllers and the impossibility to touch and feel models in the 3D environment have hampered immersion. Virtual reality applications in many areas can benefit from the introduction of haptics, such as phantom limb pain (Henriksen et al., 2017) and stroke rehabilitation (Afzal et al., 2015), (Levin et al., 2015), interactions for blind users (Schneider et al., 2018), data visualization (Englund et al., 2018), cultural heritage (Jamil et al., 2018), etc. Normally this is done through the use of custom hardware, which makes reproducibility hard and expensive.

In this paper we present an initial study on the use of the built-in vibration motors in the HTC Vive (HTC, 2016) controllers for detecting and differentiating different levels of roughness on meshes in VR. We tested our solution on fifteen participants of varying VR skill levels, using high detail 3D reconstructions of real world objects to achieve natural interactions. The participants did not see the real roughness of the object, but could only perceive it through the tactile sensation provided by the vibrotactile feedback of the controller. All users, independent of their skill level, managed to correctly distinguish the different levels of roughness of the 3D objects in a short amount of time. Thus, the research in this paper serves as a proof of concept that different levels of roughness can be successfully communicated through VR controllers without any additional hardware.

2 STATE OF THE ART

Haptic feedback has two main parts - kinesthetic and tactile feedback. Kinesthetic feedback uses the feeling coming from a person's muscles and tenders to distinguish the object that is being touched, grabbed, or held. Tactile feedback comes from the feeling of the skin sensors on the fingers and palms when an object is touched and can convey the shape, texture, and roughness. Introduction of haptic feedback to VR solutions is a non-trivial problem. This paper is focused solely on tactile feedback.

Haptic interfaces can be divided into passive and active. Both types can be useful for different cases in VR. Passive ones rely on the shape of the controller

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and try to mimic real life objects or surfaces. Examples of these can be seen in the work of (Cheng et al., 2018), (Zenner and Krüger, 2017). Active haptic feedback controller rely on moving parts, actuators and sensors, to dynamically mimic changes in the environment or the virtual objects. Examples of active haptics can be found in (Ryu et al., 2007), (Scheggi et al., 2015), (Whitmire et al., 2018). Active haptic controllers are of bigger interest to the current study.

Another possibility of active haptics is the introduction of custom tactile controllers, as seen in the work by (Choi et al., 2018), (Benko et al., 2016), (Culbertson et al., 2017) or sensors directly attached to the users' fingertips (Schorr and Okamura, 2017), (Yem et al., 2016). These controllers rely on a combination of actuators, inertial measurement units and electromagnetic coils to create a very precise sense of touch, but they require custom hardware, are normally quite bulky and are not readily available for the general public. Work is also done on directly using the controllers coming with the VR systems. Some research focuses on augmenting the controllers with additional functionality (Han et al., 2017), (Chen et al., 2016), (Ryge et al., 2017), while others rely directly on controllers' vibration (Kreimeier and Götzelmann, 2018), (Brasen et al., 2018).

We base the study in this paper on the idea that controller vibration can give an active haptics idea of the surface of 3D objects in VR and help users differentiate levels of roughness.

3 METHODOLOGY

Our proposed approach follows the research using integrated controllers, as this makes it easier to replicate and test, as well as simpler to introduce and explain to users. This means that the sensation of tactile feedback needs to be simulated to the user, so the proper information is understood. Our hypothesis is that the built-in vibrotactile features in the HTC Vive controllers can achieve this sensation, but only if the provided vibration motors are carefully controlled. In this way, VR interactions with 3D models can be achieved that are relatively close to touching a surface with a hand-held stylus in the real world.

The implementation uses Unity with the SteamVR plugin (Valve, 2015). The SteamVR API exposes three parameters for modulating the vibration of the VR controllers: amplitude, frequency and duration of the vibration. Each of the se parameters has set value constrains:

- Amplitude can take floating values between [0..1]
- Frequency accepts floating values between [0..350]
- Duration of vibration accepts floating values for the amount of seconds, with a lower bound value determined by the hardware limitations of the vibration motor

A limitation of the vibration feature is that the motors can not run all the time, therefore we have set a heuristic minimum distance of 5 mm between sampling mesh surface points before which the controller's motors are not started. This will ensure that there are pauses between the repeated activations of the haptic motor and will limited the produced vibration noise. Additionally to mitigate the possibility of noise we sample the surface of the object once every 0.1 seconds.

Figure 1: Rendering of our virtual VR stylus connected to the VR controller. The virtual stylus is used to virtually "touch" objects. The stylus is only seen in VR and does not exist on the real controller. The red rays cast from the stylus are shown for easier explanation of method and are not visible, when using the application.

Our system detects the underlying mesh roughness by calculating the angle between two sampled surface normals. To help with directing the users, in VR a 3D model of a stylus is placed on top of the Vive controller as seen in Figure 1.

Rays are cast from each vertex point of the mesh of the stylus in the direction of their surface normal vectors. The intersections of these rays with other surfaces determine the contact point between the stylus and another surface. The maximum allowed distance of intersection points is dependent on the shape of the stylus, with additional length to ensure contact at the various possible orientations. All contact points are checked starting from the tip of the stylus and going down. When two contact points are sampled, the angle between their normals is calculated and analysed. This angle can be between $[0, \pi]$, as seen in the work of (Ioannou et al., 2012), as smooth movement on the stylus on the surface is assumed.

As this is a pilot study, it was decided that the most straightforward approach is to lock the duration and leave the amplitude as the only actively adjustable quality in the experiments. Thus, the underlying surfaces can be approximated without the need to map the physical surface profile to vibration frequency. This introduces the problem that smaller surface details cannot be communicated through the vibration. To mitigate that and after analysing the difference between the normals, we simplify the underlying surface roughness to a binary classification for the vibration controller:

- Surface patches with large angle between the normals result in vibration with high amplitude, i.e., momentary, tactile ”bumps” – approximating very rough areas
- Surface patches with small angle between the normal result in low-amplitude, continuous vibration – approximating ambient roughness.

The two cases are distinguished by considering the calculated angle difference: if it is less than 6 degrees, then it is a low-amplitude vibration patch; if it is greater than 6 degrees, then it is hard vibration case. This threshold was selected heuristically after multiple trials as a believable approximation of the underlying tested surfaces. Thus our system has an dynamic component in changing the amplitude and passive component in changing between levels of predetermined frequency. The values of the frequency levels are selected after a number of internal trials:

- In case of a large normal angle the vibration duration is set to 0.075 seconds and the frequency to 16 Hz.
- In case of a small normal angle the vibration duration is set to 0.025 seconds with a frequency of 344 Hz.

The amplitude in both cases is dynamically modulated depending on the difference between the normals and the distance between the sampled points. The distance between samples is used to change the amplitude, to better approximate the feeling of dragging the stylus on a real surface. If we consider that the motion on the surface is continuous, the larger the distance between samples, taken at equal time steps, the faster the stylus is moving. Our hypothesis is that faster movement has the tendency to ”smooth out” the feeling of a rougher surfaces.

The vibrations are only sent if the user’s finger is on the trackpad since this is the part of the Vive controller where the vibrotactile feedback is felt most distinctly due to the position of the vibration motor.

4 EXPERIMENT AND RESULTS

To test how much information about the object’s roughness our proposed solution can offer users, we designed an experiment, which relied solely on the tactile information.

4.1 Experiment Setup

Three real world vases were selected and digitized using Structure from Motion (SfM) reconstruction, through the commercial software Agisoft Metashape (Agisoft, 2018). The vases were selected because of their roughness profiles. The two vases in Figure 2(a) and Figure 2(b) have a simplified roughness profile of a wave and a checkerboard pattern, which was useful for the training phase of the experiment, where users were familiarized with the setup and left to explore it, until they felt comfortable with it. These patterns provided an easy way to understand the relation between the visual appearance in VR and the tactile sensation that the controller vibration provides when interacting with the objects. A view from the initial training part can be seen in Figure 3. The real world objects were selected, to give participants an object that both has small scale roughness, but also large scale surface shape. Our hypothesis is that this will make distinguishing the different levels of roughness harder and will limit the possible effects from users learning the roughness from for example a planar shape.

The third vase, seen in Figure 2(c), was used as a basis for the experiment. Three copies of the reconstructed 3D mesh were made and each was smoothed. Three degrees of smoothing were utilized which were generated by Laplacian smoothing in Meshlab (Cignoni et al., 2008). The original reconstruction and the three smoothed copies can be seen in Figure 5. Because we were not checking if users can precisely measure roughness, but if users can distinguish and order different degrees of roughness, the degree of smoothness were chosen heuristically by experimenting with different configurations. To be sure that the vase and the three smoothed copies follow a ”smoothness progression”, a patch was taken from each of them and the root mean square height S_q was calculated from each one (Carneiro, 1995). The least rough vase was almost completely smoothed, to provide an almost blank slate compared to the other three.

The four vases were set on pedestals in VR with letters A, B, C, and D. The roughness levels, together with the set label letters and the calculated S_q are shown in Table 1. The letters are purposely randomly assigned depending on the roughness level. The ren-

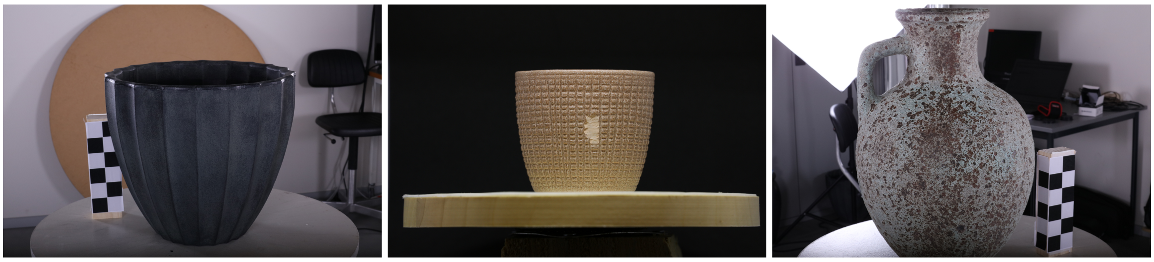
(a) (b) (c)

Figure 2: Three objects used in the experimental evaluation. The first two vases 2(a) and 2(b) are used in the initial training phase, while the third vase is used in the testing part.

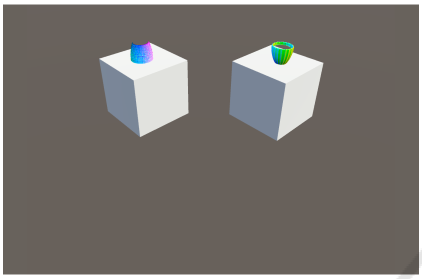

Figure 3: View from the training area, where the users could try out and test the tactile feedback on the two simple surface objects.

Table 1: The roughness levels of each of the four objects, together with the labels denoting them and the calculated root mean square height S_q. The letters are given at random to the different roughness levels and are used when testing

Roughness	S_q [mm]	Label
Most	0.5569	D
Second	0.5114	A
Third	0.4784	B
Least	0.0304	C

dering of their meshes was deactivated with only the colliders left. On top of each of them a completely smooth model was rendered, so users had no way of visually seeing the real roughness. The testing setup can be seen in Figure 4. Between each user test the positions of the vases were randomly rotated, but the combination between letter and roughness was not changed. We rotate the vases to avoid directional bias from users, when checking which object they interact most with. This bias can manifest in right or left handed participants going always to the object on their left or right, which without the rotation can always be the same. To help directing the attention of the users, a specific patch of all the vases was selected, where the roughness is particularly pronounced and colored red. A close-up of underlying roughness of the patch is shown in Figure 4, while the users just saw a smooth red surface.

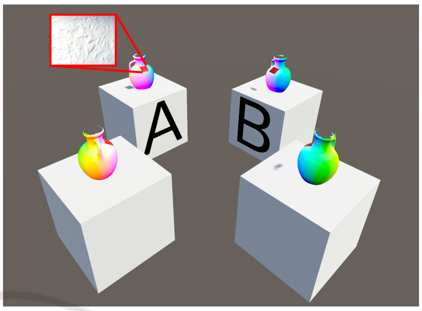

Figure 4: View from the testing area, with the four identically looking vases. Each of the vases has the collider of a object with different level of roughness. The objects are labeled and a red patch is selected on them, to help directing the attention of the users. A close-up of the underlying patch roughness is shown for easier understanding and is not visible for the users. The objects are rotated between users.

4.2 Participants and Captured Data

Fifteen participants tested the system by using the experimental setup. The users had an age between 23 and 35 years and varying degrees of proficiency using VR. Each user was left to first explore the training part of the experimental VR setup, while the facilitator explained to them how to use the system. Once the user was comfortable, they were teleported to the testing part, where they were asked to try to order the four identically looking vases depending on the perceived roughness profile, when they interacted with them. The users had unlimited time and were instructed to use the specified red patch on the vases if they had a hard time distinguishing the objects. Once the users were ready, they gave their idea of the ordering of the vases. The time between the start of the experiment and the end was taken, as well as the amount of times the user had interacted with each of the four vases.

(a) Label D (b) Label B (c) Label A (d) Label C

Figure 5: The vase used for the testing phase (a), together with the other three progressively smoother copies (b) to (d). The labels from A to D were set as seen in Table 1.

4.3 Results and Discussion

All fifteen participants could successfully order the objects from roughest to smoothest. The average completion time was 124.8 seconds, with a standard deviation of 68.3 seconds. The large standard deviation was caused by three participants, who took more than 200 seconds to complete the experiment. All three of the participants had little or no experience in using VR, thus, their slower completion time can be attributed to some extend to their inexperience. The completion times for all users, depending on their proficiency, can be seen in Figure 6. Here it can be seen that some of the people with no proficiency took a lot of time, due to not being fully comfortable using a VR controller and overall a lot more variation is seen in their times. People with high proficiency have a lower spread and do not require a lot of time to distinguish between roughness levels successfully.

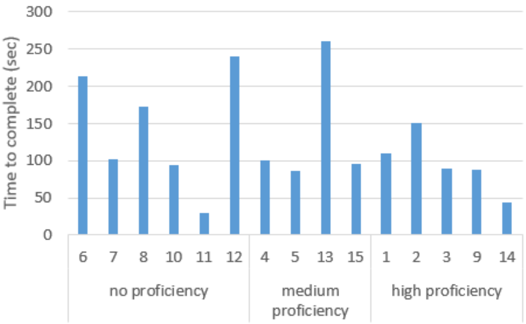

Figure 6: Completion times for each user, grouped by the three VR proficiency levels.

The number of times users interacted with each of the four objects can give an overview, which object was the most difficult to categorize. The results for each user, depending on their proficiency level, for each of the objects can be seen in Figure 7. These results reflect the completion times, discussed above, with some deviations, showing that some users were interacting with the objects more, while other were more passive. Again users with no proficiency required more interactions and focus more on the smoothest object *C*.

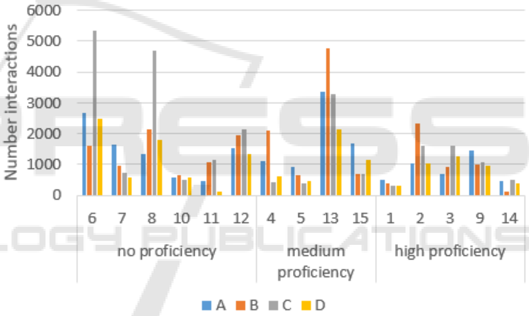

Figure 7: Number of times users interacted with each of the four objects, grouped by the three VR proficiency levels. Each time users touched the objects, this is counted as an interaction.

Table 2 expands more on the captured results. The values in *Most Interactions* denote the number of times each of the four objects has been interacted with the most by the users. On the other hand, *Least Interactions* denotes the number of times each object has been interacted with the least amount of times. The table shows that the object with the most roughness *D*, has never been interacted the most times and has been interacted the least amount of time by most users. This shows that people generally really easily decided how rough it was and did not need more interaction. On the other hand, the smoothest object *C* is both the most interacted object by the most people, as well as the second least interacted object. This points to the fact that the order in which users interacted with the objects is important for discerning their correct roughness. As expected, starting with the roughest object is most beneficial. Finally, the two in-between objects *A* and *B*, had approximately the same level of difficulty, but once users made up their minds on the most and least rough, they could decide on the in-between ones easier. On top of that some participants commented on that they could hear the haptic motors spin, those who did comment on it were told to try and ignore it. But it is unclear if it had an impact on the results.

Table 2: The most and least interacted with labeled objects. The results are created from the fifteen participants.

	A	B	C	D
Most Interactions	5	4	6	0
Least Interactions	3	3	4	5

5 CONCLUSION AND FUTURE WORK

Our experiment demonstrated that information about the surface roughness of 3D objects can be communicated through the use of tactile sensation achieved by the built-in vibration capabilities of HTC Vive controllers. With the help of a virtual VR stylus, users can use the same natural interactions as in real life to "feel" the surface of an object. The preliminary experiment demonstrated that users can order objects by their perceived vibration surface roughness without visual cues. The test showed that users could relatively fast decide which is the roughest of multiple, visually identical objects, as well as the smoothest and order them always correctly.

There are some limitations of this preliminary study. The limited scope of the test and the limited number of participants resulted in results which are too homogeneous and do not show enough variation to further improve the system. To address these shortcomings, additional experiments are planned. In particular, we want to investigate the influence of amplitude and frequency of the vibrotactile feedback on the perceived roughness. Another experiment could explore how much of an impact the sound of the controller has on the haptic feeling as some of the test participants mentioned that they could hear different noises from the motors in the controllers.

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