IEEE Access
Multidisciplinary ⁝ Rapid Review ⁝ Open Access Journal

Received May 4, 2018, accepted July 18, 2018, date of publication July 23, 2018, date of current version August 15, 2018.

Digital Object Identifier 10.1109/ACCESS.2018.2858268

Pseudo-Shape Sensation by Stereoscopic Projection Mapping

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This work was supported by the JSPS KAKENHI under Grant JP15H05925.

ABSTRACT Pseudo-haptics employ visual information rather than active haptic devices to generate haptic sensations by exploiting a cross-modal effect in the brain between visual and haptic sensations. To date, little research has focused on pseudo-haptics in the projection mapping research field. This paper investigates the effect of stereoscopic projection mapping on haptic shape perception. We developed a perspective projection mapping technique that visually deforms a physical surface and translates a finger touching the surface. Psychophysical experiments were conducted to investigate the relationship between the degree of deformation and the haptically perceived shape relative to the height and curvature radius. The results indicate that the proposed stereoscopic projection mapping technique can manipulate haptic shape sensation, i.e., perceived deformation increases as the projected deformation increases. In addition, we found that the perceived shape was in between the physical and projected shapes, and converged to both the upper and lower limits. Further analysis revealed that the pseudo-haptic sensation of the curvature radius was stronger than that of the height.

INDEX TERMS Pseudo-haptics, projection mapping, shape perception, spatial augmented reality.

I. INTRODUCTION

Projection mapping or spatial augmented reality (AR) refers to techniques in which computer graphics (CG) are projected onto a real object to manipulate its appearance [1]. These techniques generate the illusion of virtual modification of the object's physical surface and create a realistic representation of a virtual reality (VR) in the real world. Projection mapping has been integrated and applied in many fields, such as education [2], vehicle design [3], art creation [4], daily life support (e.g., searching everyday objects [5]), makeup [6], virtual restoration of historical objects [7], and entertainment (e.g., games [8] and theme parks [9]). However, current technologies are limited to controlling the visual property of the surface materials. To render other modalities, such as haptics for consistent augmentation, additional dedicated devices are required.

Haptic sensation is an important modality in AR systems; thus, many researchers have focused on developing haptic displays that provide physical force feedback. However, AR systems that can reproduce complex haptic sensations tend to be complicated and large. As an alternative method, pseudo-haptics have been attracted attention as a potential solution to provide haptic information without the use of active haptic devices. Pseudo-haptics generate haptic sensations using only visual information based on a haptic illusion triggered by a cross-modal effect in the human brain between visual and haptic sensations [10]. However, research into pseudo-haptic AR has been limited to video see-through systems that manipulate the visual information of a real scene captured by a camera, which is displayed on a flat panel or head-mounted display (HMD). This means that pseudo-haptics have been mostly limited to ''de-located'' simulations, where manipulation and visual spaces are separate. Projection mapping is a solution to the ''de-located'' problem, because it can superimpose the manipulation and visual spaces. However, to date, few studies have investigated pseudo-haptics in projection mapping.

In this paper, we introduce a projection mapping technique that does not require haptic devices to visually manipulate the haptic shape sensation of a user touching a physical object. We used a consumer-grade stereoscopic projector to modify the apparent shape of a touched object and translate a finger touching the object (hereafter, touching finger). Specifically, we implemented a projection mapping system that modifies the height and curvature radius of a projected surface, which we consider to be major components of a shape.

We performed psychophysical experiments to investigate how these visual augmentations alter the haptic perception of the shape due to the cross-modal effect. To the best of our knowledge, this is one of the very first attempts to explore the potential of pseudo-haptics in a ''co-located'' simulation. The proposed system is illustrated in Figure 1.

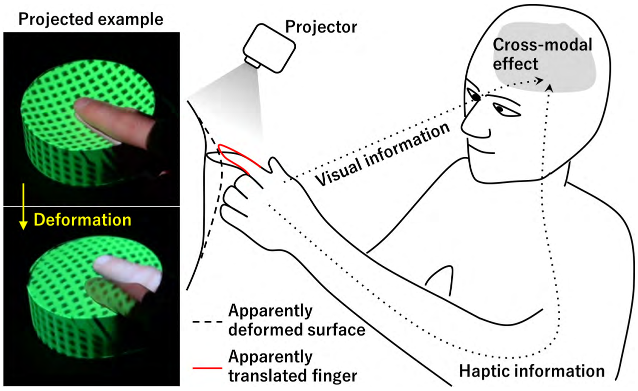


FIGURE 1. **Manipulating haptic shape perception of a surface by visually deforming it using stereoscopic projection mapping.**

II. RELATED WORK

Pseudo-haptics are caused by multi-sensory integration of visual and haptic sensations in the human brain and have been studied extensively in psychological research [11], [12]. Following the pioneering work by Lecuyer *et al.* [10], VR systems have applied pseudo-haptics to provide haptic sensations by presenting CG that cause inconsistency between visual and haptic sensations [13]. From an engineering perspective, an important advantage of pseudo-haptics is that they do not require haptic feedback hardware.

Recently, pseudo-haptics have been investigated extensively in AR environments [14], [15]. Here, we focus on studies that manipulated haptic shape perception. Kitahara *et al.* [16] reported that haptic sharpness perception for an edge can be altered by visually presenting the edge with a different curvature using a video see-through HMD. Ban *et al.* [17] found that haptic curvature perception for a physical surface can be altered by visually presenting the surface with a different curvature than that of the physical surface and displacing the position of a fingertip touching the surface. Most previous studies into pseudo-haptic AR have applied video see-through displays because real surface can easily be visually replaced or modified using CG.

However, pseudo-haptics in a projection mapping system has not been thoroughly investigated because controlling the appearance of a real scene is difficult. In projection mapping research, several radiometric compensation methods have been developed to project desired appearances onto textured surfaces [18]. However, even the latest technique [19] suffers from the limited dynamic range of current projection systems, and thus cannot perfectly control the appearance of a real scene. Nevertheless, some studies have confirmed some pseudo-haptic sensations in projection mapping systems. Ho *et al.* [20] found that thermal perception was altered by changing the color of the hand using projected imagery. Punpongsanon *et al.* [21] manipulated softness perception by modifying the optical flow of a surface using projection mapping. However, to the best of our knowledge, no study has investigated how haptic shape perception is affected by projected imagery.

In this study, we developed a projection mapping technique to modify the haptic shape perception of a touched object. Then, we examined how the proposed technique worked under the assumption that the desired appearance was not achieved on the target surface. We conducted psychophysical experiments to investigate the relationships between the parameters of projected visual effects and the haptic shape perception of the projected object relative to its height and curvature radius, respectively.

III. ALTERING SHAPE PERCEPTION USING STEREOSCOPIC PROJECTION MAPPING

Here, we describe how the haptic shape perception of a touched real object is altered using projection mapping. Previous pseudo-shape research using video see-through AR [17] replaced the original surface captured by a camera with a deformed surface on a flat panel display. In addition, the touching finger region extracted in the captured image was deformed such that the fingertip touched the deformed surface in the displayed image. In this study, we employed this approach to alter haptic shape perception through projection mapping. Although the previous study displayed images on a flat panel, in our study, we displayed the deformed surface and translated finger on a three-dimensional (3D) surface in real space.

We developed a stereoscopic projection mapping technique to visually deform a touched surface and translate a touching finger image such that the fingertip was placed on the deformed surface. The visual information projected on the real surface and finger must appear geometrically correct to both a stationary and head-tracked moving observer. To achieve this, we employed the two-pass projective texture scheme shown in Figure 2 to generate projection images [22].

First, here, we assume to measure the 3D shape of the scene, including the projection surface and user's finger, the pose of the projector relative to the surface, and the user's eye position (Figure 2(1)). The positions of the user's finger and eye are measured in real-time; thus, the user can move them while using the system. Second, we capture a target scene from the eye position in a virtual space (Figure 2(2)). As the target scene, we deformed the surface and translated the finger position. Third, in an initial projective texturing pass, we applied perspective projection mapping of the captured image onto the scene from the eye position in the virtual space (Figure 2(3)). This projected result was then captured from a virtual camera placed at the projector's position. Fourth, in the second pass, we projected the captured image onto the real scene from the real projector (Figure 2(4)).

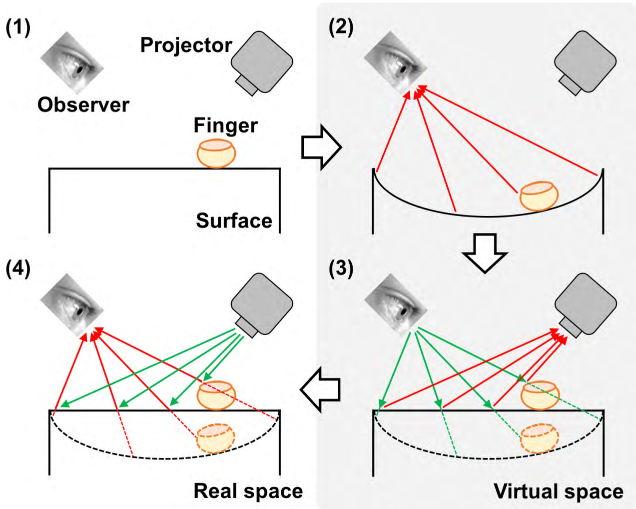


FIGURE 2. Two-pass projective texture method.

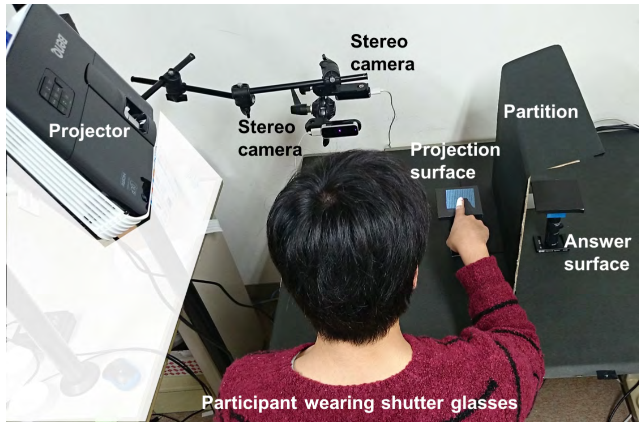
As a result, the user's eye can observe the perspectively correct appearance of the target scene. We performed this process twice, once for each of the user's eyes, in a frame to provide binocular stereopsis. Note that we used a consumer-grade stereoscopic projection system to show the projected images for each eye independently.

IV. PSYCHOPHYSICAL STUDY INTO HAPTIC HEIGHT PERCEPTION

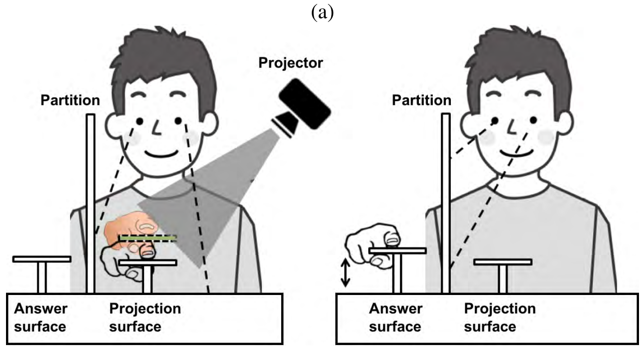
We implemented a system that visually controlled the height of a planar surface using stereoscopic projection mapping to investigate how the height difference between physical and projected surfaces affects the haptic height sensation of a participant touching the surface.

A. EXPERIMENTAL SYSTEM AND PROCEDURE

Figure 3(a) shows the experimental setup. Here, we prepared two planar surfaces (10 × 10 cm^2), one for projection and one to answer the perceived height. The color of the surfaces was uniform dark gray, and the heights were adjustable. A stereoscopic projector (BenQ TH682ST, 1,920 × 1,080 pixels, 60 Hz, 3,000 ANSI lumen) was placed facing downward to visually deform the projection surface. The participant wore active shutter glasses to observe binocular stereoscopic images on the surface. A stereo camera (Leap Motion Controller) was used to measure the pose of the index finger of the participant's right hand (this finger touched the projection surface). Assuming that the shape of the index finger is a simple cylinder, we used the pose information to estimate the shape of the index finger for our stereoscopic projection mapping technique (Section III). Another stereo camera was used to track retro-reflective markers attached to the glasses to determine the participant's viewpoint. The system was controlled by a PC (CPU: Intel Core-i7-930 2.80 GHz, RAM: 6 GB, GPU: AMD Radeon HD 5570). The horizontal distance between the two planar surfaces was 10 cm. We placed a partition between the surfaces so that the answer surface was not viewable by the participant. Note that this experiment was conducted in a dark room.



(a)



(b)

FIGURE 3. System configuration for the study of perceived height: (a) experimental setup, (b) participant touching the projection and answer surfaces.

We applied a magnitude estimation method to measure the haptically perceived height when the participant touched a visually deformed surface (Figure 3(b)). We asked each participant to touch the projection and answer surfaces repeatedly using the index finger of the right hand. If the haptically perceived height of the answer surface differed from that of the projection surface, the participant adjusted the height of the answer surface such that it was perceptually the same as that of the projection surface. We asked the participant to observe the projected image when touching the projection surface, and we allowed the participant to freely move their index finger on the surface and their head.

The physical height of the projection surface was set to 17 cm. We prepared 11 experimental conditions relative to the projected height (i.e., the modified height): 12, 13, 14, 15, 16, 17, 18, 19, 20, 21 and 22 cm. To prevent the participant from remembering the physical height throughout the experiment, we prepared dummy physical heights (15 and 16 cm). Consequently, 22 conditions were prepared for each participant, i.e., 11 projected heights × two physical heights (17 cm and a randomly selected dummy height). Each participant performed the experiment once for each condition, and the order of the conditions was randomized among participants. Note that a uniform gray image was projected when the projected and physical heights were the same.

B. RESULTS

Ten subjects participated in this experiment, and each experimental condition required approximately two minutes on average. Figure 4 shows the means and standard deviations of the subjective magnitudes of the haptically perceived height. Here, we plot the results of the 11 height conditions where the physical height of the projection surface was 17 cm. A one-way analysis of variance (ANOVA) showed the main effect in the height difference ($F(10, 90) = 38.69, p < 0.01$).

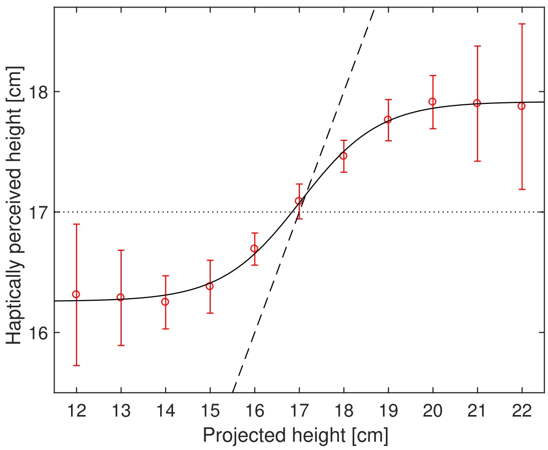


FIGURE 4. **Average and standard deviation of haptically perceived height for each projected height (red circle with bar). Solid and dotted lines represent the fitted logistic function and physical height of the projection surface (i.e., 17 cm), respectively. Here, the perceived and projected heights are the same on the dashed line.**

When the projected and physical heights were the same (i.e., a uniform gray image was projected), the average haptically perceived height was 17.09 cm with a standard deviation of 0.14 cm. Thus, as a baseline, we confirmed that the participants' haptic height perceptions were reliable and accurate. From the results obtained when the projected heights were other than 17 cm, we confirmed that the haptically perceived height was altered by the stereoscopic projection mapping. We found a consistent trend, i.e., the perceived height became lower (or higher) than the physical height when the projected height was lower (or higher). Specifically, the perceived height was in between the physical and projected heights, which are indicated by the dotted and dashed lines, respectively, in Figure 4.

We considered that the perceived height converged to both the upper and lower limits. Then, we fit the following logistic function to the results using the Levenberg-Marquardt method:

$$y = \frac{K}{1 + e^{-r(x-x_0)}} + c, \tag{1}$$

where y and x represent the perceived and projected heights, respectively, and K, r, x_0, and c are the coefficients of the logistic function. As a result, we obtained $K = 1.66$, $r = 1.13$, $x_0 = 17.02$, and $c = 16.26$ with an averaged absolute residual of 0.031. The fitted function is visualized as the solid line in Figure 4.

V. PSYCHOPHYSICAL STUDY INTO HAPTIC CURVATURE RADIUS PERCEPTION

We also implemented a system that deformed a curved surface, where its curvature radius was altered by the stereoscopic projection mapping technique. With this system, we investigated how the difference in curvature radius between the physical and projected surfaces affected the participant's haptic curvature radius sensation when touching the surface.

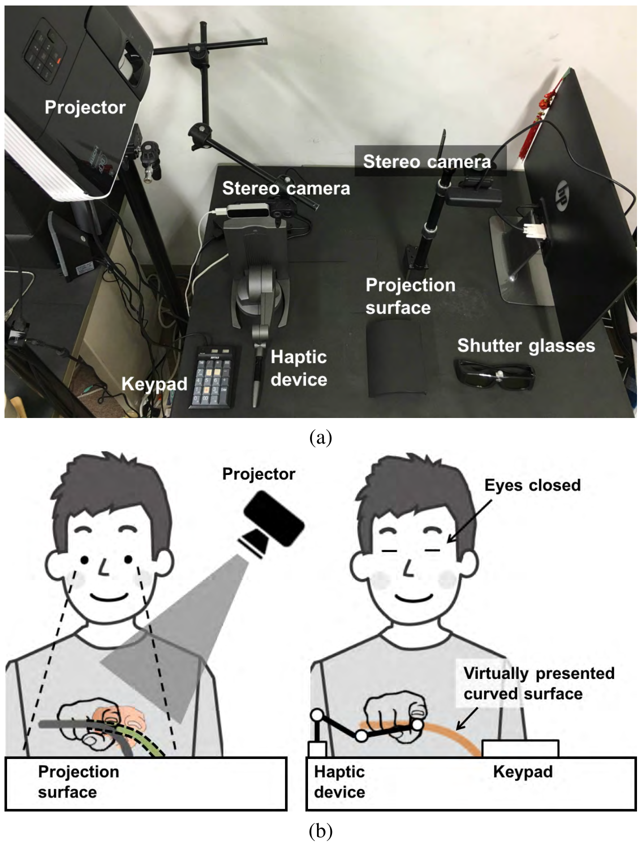


FIGURE 5. **System configuration for the perceived curvature radius study: (a) experimental setup and (b) illustration of participant touching the projection surface and haptic device.**

A. EXPERIMENTAL SYSTEM AND PROCEDURE

Figure 5(a) shows the experimental setup. The same equipment used in the previous experiment (Section IV) was used in this experiment, with the exception of the projection surface and stereo camera. We prepared a uniform dark gray curved surface with a curvature radius of 13 cm as the projection surface. Note that we did not prepare an answer surface. Instead, we used a force feedback device (Geomagic Touch X) to virtually present curved surfaces with different curvature radii for answering. The experiment was also conducted in a dark room.

We applied a magnitude estimation method to measure the haptically perceived curvature radius when the participant touched the visually deformed surface (Figure 5(b)). We asked each participant to touch the projection surface and use the haptic device repeatedly with the index finger of their right hand. If the haptically perceived curvature radius presented by the haptic device differed from that of the projection surface, the participant adjusted the curvature radius using a keypad (up: larger curvature radius; down: smaller curvature radius) to perceptually match the curvature radius of the projection surface to that presented by the haptic device. When the participant touched the projection surface, they were asked to observe the projected image. Note that the participant was permitted to freely move their head and the index finger touching the surface. When the participant used the haptic device, we asked them to close their eyes so that they relied on only the haptic sensation.

TABLE 1. Experimental conditions in psychophysical study into perception of curvature radius.

Physical curvature radius [cm]	Virtual curvature radius [cm]
7	4, 5, 6, 7, 8, 9, 10
10	7, 8, 9, 10, 11, 12, 13
13	9, 10, 11, 12, 13, 14, 15, 16, 17

We prepared 23 experimental conditions by combining multiple physical curvature radii of the projection surface and virtual curvature radii presented by the haptic device (Table 1). Note that the 14 conditions in which the physical curvature radius was either 7 or 10 cm were used as dummy conditions to prevent the participant from remembering the physical curvature radius throughout the experiments. We analyzed the haptically perceived curvature radii for the conditions where the physical curvature radius was 13 cm. Each participant performed the experiment once for each condition, and the order of the conditions was randomized among participants. Note that a uniform gray image was projected when the projected and physical curvature radii were the same.

B. RESULTS

Ten subjects participated in the experiment, and experimenting with each condition took approximately two minutes on average. Figure 6 shows the means and standard deviations of the subjective magnitudes of the haptically perceived curvature radius. We plot the results of the nine conditions where the curvature radius of the projection surface was 13 cm in Figure 6. A one-way ANOVA showed the main effect in the height difference ($F(8, 72) = 71.0, p < 0.01$).

When the projected and physical curvature radii were the same (i.e., a uniform gray image was projected), the average of haptically perceived curvature radius was 12.82 cm with a standard deviation of 0.39 cm. Thus, as a baseline, we confirmed that the haptic curvature radius perception of the participants was reliable and accurate. From the results obtained when the projected curvature radius was other than 13 cm, we confirmed that the haptically perceived curvature radius was altered by the stereoscopic projection mapping. Here, we found a consistent trend, i.e., the perceived curvature radius became smaller (or larger) than the physical curvature radius when the projected curvature radius was smaller (or larger). Specifically, the perceived curvature radius was in between the physical and projected curvature radii, which are indicated by the dotted and dashed lines, respectively, in Figure 6.

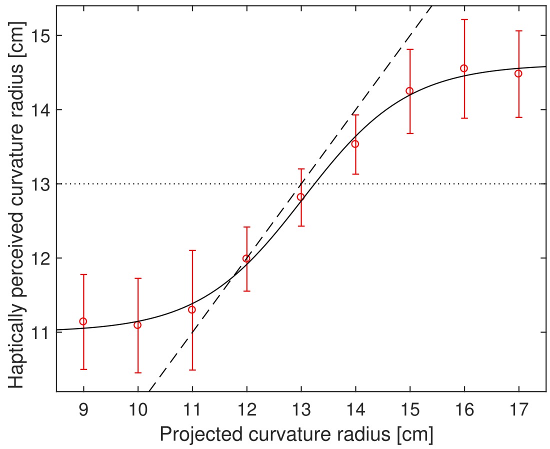


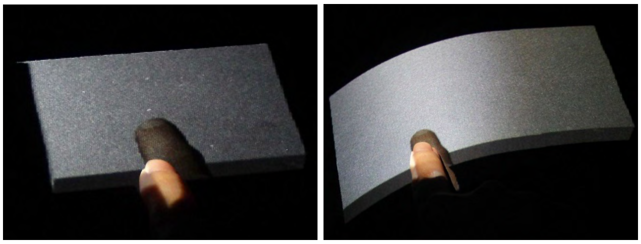
FIGURE 6. Average and standard deviation of perceived height for each projected curvature radius (red circle with bar). Solid and dotted lines represent the fitted logistic function and physical curvature radius of the projection surface (i.e., 13 cm), respectively. The perceived and projected curvature radii are the same on the dashed line.

We considered that the perceived curvature radius converged to both larger and smaller limits; thus, we fit the logistic function (Equation (1)) to the results using the Levenberg-Marquardt method. As a result, we obtained $K = -3.61$, $r = -1.04$, $x_0 = 13.04$, and $c = 14.61$ with an averaged absolute residual of 0.075. The fitted function is visualized as the solid line in Figure 6.

VI. DISCUSSION

To the best of our knowledge, this work is the first attempt to explore the applicability of a projection-based approach to manipulate the haptic perception of shape based on pseudo-haptics. The results of the psychophysical studies suggest that we can manipulate haptic shape sensation using our stereoscopic projection mapping technique.

As a disadvantage of projection mapping compared to other AR approaches, the desired appearance of the deformed surface is not always displayed correctly on the surface because surface and finger textures disturb the color of the projected results. Even the latest radiometric compensation technique cannot perfectly cancel the textures due to the limited dynamic range of a projector [19]. In our studies, the finger color was visible, as shown in Figure 7. We believe it is an interesting and important finding that the haptic shape sensation was still altered even when the desired appearance (i.e., deformation effect) was not displayed perfectly.



(a) (b)

FIGURE 7. Projected appearances in the psychophysical studies into (a) haptic height perception and (b) haptic curvature radius perception.

The deviation at the inflection point of the fitted logistic function indicates how strongly stereoscopic projection mapping affected the participants' haptic shape sensations. If it is close to 1.0 (corresponding to the dashed lines in Figures 4 and 6), the perceived and projected surface shapes are nearly the same. The deviations shown in Figures 4 and 6 are 0.47 and 0.94, respectively. Thus, the pseudo-haptic sensation of the curvature radius was stronger than that of the height.

VII. CONCLUSION

This study has examined how stereoscopic projection mapping affects haptic shape perception in the context of pseudo-haptics. We developed a perspective projection mapping technique that visually deforms a physical surface and translates a finger touching the surface. In two psychophysical studies, we investigated the relationship between the degree of deformation and the haptically perceived shape relative to height and curvature radius. The results suggest that our stereoscopic projection mapping technique can manipulate haptic shape sensation. The perceived deformation became larger when the projected deformation was larger. We also found that the perceived shape was in between the physical and projected shapes, and converged to both the upper and lower limits. Further analysis revealed that the pseudo-haptic sensation of the curvature radius was stronger than that of the height.

Note that this study only considered simple shapes. Thus, in future, to develop practical application systems, such as product design support and education systems, we must further investigate pseudo-shape sensations for more complex shapes.

REFERENCES

[1] O. Bimber and R. Raskar, *Spatial Augmented Reality: Merging Real and Virtual Worlds*. Boca Raton, FL, USA: CRC Press, 2005.

[2] D. Iwai, R. Matsukage, S. Aoyama, T. Kikukawa, and K. Sato, "Geometrically consistent projection-based tabletop sharing for remote collaboration," *IEEE Access*, vol. 6, pp. 6293–6302, 2017.

[3] C. Menk, E. Jundt, and R. Koch, "Visualisation techniques for using spatial augmented reality in the design process of a car," *Comput. Graph. Forum*, vol. 30, no. 8, pp. 2354–2366, 2011.

[4] M. Flagg and J. M. Rehg, "Projector-guided painting," in *Proc. 19th Annu. ACM Symp. User Interface Softw. Technol.*, 2006, pp. 235–244.

[5] D. Iwai and K. Sato, "Document search support by making physical documents transparent in projection-based mixed reality," *Virtual Reality*, vol. 15, nos. 2–3, pp. 147–160, 2011.

[6] A. H. Bermano, M. Billeter, D. Iwai, and A. Grundhöfer, "Makeup lamps: Live augmentation of human faces via projection," *Comput. Graph. Forum*, vol. 36, no. 2, pp. 311–323, 2017.

[7] D. G. Aliaga, A. J. Law, and Y. H. Yeung, "A virtual restoration stage for real-world objects," *ACM Trans. Graph.*, vol. 27, no. 5, p. 149, 2008.

[8] B. R. Jones, H. Benko, E. Ofek, and A. D. Wilson, "IllumiRoom: Peripheral projected illusions for interactive experiences," in *Proc. ACM SIGCHI Conf. Hum. Factors Comput. Syst.*, 2013, pp. 869–878.

[9] M. R. Mine, D. Rose, B. Yang, J. van Baar, and A. Grundhöfer, "Projection-based augmented reality in disney theme parks," *Computer*, vol. 45, no. 7, pp. 32–40, 2012.

[10] A. Lecuyer, S. Coquillart, A. Kheddar, P. Richard, and P. Coiffet, "Pseudo-haptic feedback: Can isometric input devices simulate force feedback?" in *Proc. Virtual Reality*, 2000, pp. 83–90.

[11] I. Rock and J. Victor, "Vision and touch: An experimentally created conflict between the two senses," *Science*, vol. 143, no. 3606, pp. 594–596, 1964.

[12] M. O. Ernst and M. S. Banks, "Humans integrate visual and haptic information in a statistically optimal fashion," *Nature*, vol. 415, no. 6870, pp. 429–433, 2002.

[13] A. Lécuyer, "Simulating haptic feedback using vision: A survey of research and applications of pseudo-haptic feedback," *Presence, Teleop. Virtual Environ.*, vol. 18, no. 1, pp. 39–53, 2009.

[14] A. Pusch, O. Martin, and S. Coquillart, "HEMP-hand-displacement-based pseudo-haptics: A study of a force field application," in *Proc. IEEE Symp. 3D User Interfaces*, Mar. 2008, pp. 59–66.

[15] A. Iesaki, A. Somada, A. Kimura, F. Shibata, and H. Tamura, "Psychophysical influence on tactual impression by mixed-reality visual stimulation," in *Proc. IEEE Virtual Reality Conf. (VR)*, Mar. 2008, pp. 265–266.

[16] I. Kitahara, M. Nakahara, and Y. Ohta, "Sensory properties in fusion of visual/haptic stimuli using mixed reality," in *Advances in Haptics*, M. H. Zadeh, Ed. Rijeka, Croatia: InTech, 2010, ch. 30. [Online]. Available: http://dx.doi.org/10.5772/8712

[17] Y. Ban, T. Kajinami, T. Narumi, T. Tanikawa, and M. Hirose, "Modifying an identified curved surface shape using pseudo-haptic effect," in *Proc. IEEE Haptics Symp. (HAPTICS)*, Mar. 2012, pp. 211–216.

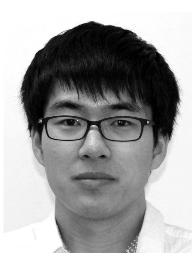
[18] O. Bimber, D. Iwai, G. Wetzstein, and A. Grundhöfer, "The visual computing of projector-camera systems," *Comput. Graph. Forum*, vol. 27, no. 8, pp. 2219–2245, 2008.

[19] A. Grundhöfer and D. Iwai, "Robust, error-tolerant photometric projector compensation," *IEEE Trans. Image Process.*, vol. 24, no. 12, pp. 5086–5099, Dec. 2015.

[20] H.-N. Ho, D. Iwai, Y. Yoshikawa, J. Watanabe, and S. Nishida, "Combining colour and temperature: A blue object is more likely to be judged as warm than a red object," *Sci. Rep.*, vol. 4, Jul. 2014, Art. no. 5527.

[21] P. Punpongsanon, D. Iwai, and K. Sato, "*SoftAR*: Visually manipulating haptic softness perception in spatial augmented reality," *IEEE Trans. Vis. Comput. Graphics*, vol. 21, no. 11, pp. 1279–1288, Nov. 2015.

[22] R. Raskar, G. Welch, M. Cutts, A. Lake, L. Stesin, and H. Fuchs, "The office of the future: A unified approach to image-based modeling and spatially immersive displays," in *Proc. ACM 25th Annu. Conf. Comput. Graph. Interact. Techn.*, 1998, pp. 179–188.



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