仮想環境におけるレイキャスティングを用いたインタラクティブ・サーフィスの設計と没入型フォトブラウザへの応用

高階知巳，伊藤　充，長浦　仁，若林英佑

Design of Curved Raycasting-based Interactive Surfaces in Virtual Environments and Its Application to an Immersive Photo Browser†

Tomomi TAKASHINA, Mitsuru ITO, Hitoshi NAGAURA and Eisuke WAKABAYASHI

3 次元ユーザインタフェースが一般的になると，素早く操作でき信頼性の高い選択方法・操作方法が必要とされる．我々は仮想空間の中でレイキャスティングを用いて操作する仮想ディスプレイ（インタラクティブ・サーフィス）が曲率を制御できる曲面を持っているとして，その操作性を評価する．ユーザはヘッドマウントディスプレイを装着し，その中に見えるインラクティブ・サーフィスをハンドコントローラにより操作する．我々は操作にかかる時間と操作の精度を様々な条件の曲面に対して調査した．異なる曲面の条件に対してのユーザの操作能力を調べるために，完全な平面を含む異なる曲率を持った曲面を用いて実験を行った．実験結果から，表示面の曲率を変えることで，最も効果的な場合には，完全な平面に対して28%精度が良く，15%高速にポインティングできることがわかった．この結果を応用し，我々は，曲面に写真を配置する没入型写真ブラウザを設計・実装した．これらの結果は，一般的な 2 次元スタイルのアプリケーションにおいて，空中ポインティング機能を持った，曲面のインタラクティブ・サーフィスに適用することが可能である．

As three-dimensional user interfaces become more popular, quick and reliable aerial selection and manipulation are desired. We evaluated a virtual curved display (interactive surface) with controllable curvature based on raycasting. The user operates the surface by pointing using a head-mounted display and grip-type controller. We investigated the operation speed and accuracy of curved interactive surfaces under various presentation conditions. To investigate the users' operation ability for different curved conditions, we experimented with multiple surface curvature radii, including completely flat conditions. The experimental results showed that varying the curvature of the display improved the pointing accuracy by 28% and the speed by 15% over the flat surface in the most effective cases. By utilizing the analysis results, we designed and implemented an immersive photo browser in which photos are placed on a curved surface. These findings can be applied to curved interactive surfaces with mid-air pointing for generic two-dimensional-style applications.

Key words 仮想空間，インタラクティブ・サーフィス，仮想ディスプレイ，空中ポインティング，レイキャスト，写真ブラウザ
virtual reality, interactive surface, virtual display, mid-air pointing, raycasting, photo browser

1 Introduction

Displays in a virtual environment (VE) provide a fully programmable workspace without the need for large physical spaces. The advantage of such virtual workspaces is that they allow us to adopt findings regarding operational efficiency from physical large screen display design [4]. Large workspaces display a large amount of information, however manipulation through the pointing interface is difficult. One of the solutions to these problems is to design a curved workspace [1], [2].

Although such large displays are difficult to operate, the raycasting technique can be used to interact with objects in a virtual world, which is advantageous compared to pointing in the real world [3], [6]. Therefore, we compared the operational efficiencies of flat and curved surfaces assuming that raycasting was used in VEs.

In this study, we evaluated curved virtual interactive sur-

† This paper is based on [5] and includes a new section for an application of the proposed method.

faces and investigated the effects of curvature, size, and presentation distance on operational efficiency. The operation was performed using ray casting to point away from the user. The design parameters were analyzed based on Fitts' law, which accounts for the amount of ray travel.

The remainder of this paper is organized as follows. First, we present a theoretical analysis of the operation time for flat and curved surfaces. Next, we describe experiments to evaluate the operational efficiency of the interactive surface with respect to pointing and clicking on position and size. We then introduce our implementation of an immersive photo browser based on the results of the experiments. Finally, we conclude this paper.

2 Operation Time Analysis by Fitts's Law

Shupp investigated the curvature of a real large display and found that users could operate it 30% faster than flat displays [4]. In a virtual world, a display shape can be designed without any physical restrictions.

We compared the operational efficiencies of flat and curved surfaces. We conducted a theoretical analysis of the time required to point to the leftmost and rightmost selective targets using Fitts's law: $T = a + b\log_2(1+ D/W)$. For the analysis of pointing via raycasting, the ray is controlled by changing the angle of the hand. Thus, we used W and D as the values converted into angles. Let T^f and T^c be the times required to point to the edge targets on a flat panel and curved panel, respectively. Fig. 1(a) and (b) show the schematics of flat and curved surfaces and the operations based on the assumption of one-dimensional movements. If we assume $a = 0$, the speedup of a curved surface can be expressed as

$$S^* = (T^f - T^c)/T^f = 1 - \log(1 + D/W)/\log(1 + D/W).$$

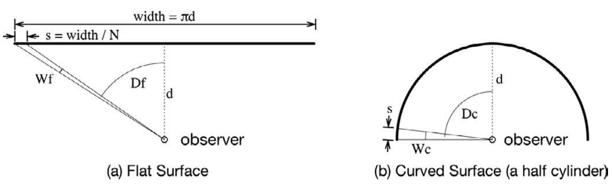


Fig. 1 Models for Interactive Surfaces. The user's operation angle is controlled by the curvature radius of the virtual surface.

3 Experiment

To evaluate the suitability of different shapes for an immersive interactive surface, we conducted within-subject experiments to investigate the effects of display size and curvature radius on the selection of a grid of visual objects.

The participants were required to perform pointing tasks in a virtual space, as shown in Fig. 2. A virtual interactive surface with a grid was shown to each participant at a time (Fig. 3). The shape of the surface is defined by a combination of several parameters (Fig. 4). The grid had the same pitch in both the horizontal and vertical directions. The width was calculated from the height such that the aspect ratio tended to be 16:9. We employed grids of different sizes to vary the pointing difficulty.

The surfaces have the same arc length (corresponding to the width w of a flat surface) for different curvature radii r_c when the height is fixed. The viewing distance was also varied (Fig. 4(a)). To investigate the percentage of correct responses and the operation time for the user's average operation angle, the length of the presentation distance was varied to be longer and shorter than the minimum radius of curvature.

The participant sat on a chair, put on an Oculus Rift S, and held two Oculus Touch controllers, as shown in Fig. 2(b). The software for this experiment was implemented in Unity. Stimuli were provided to the participants as colored squares for each surface condition. Eight healthy adults (age, 38 ± 10 years; gender, male) participated in the experiment.

The number of surface conditions is 90 (3 × 5 × 2 × 3). A surface was chosen in order from the combination table of the four attributes. Because the first factors vary the fastest (refer to Fig. 4(c)) in the combination table and flat conditions scatter in the surface sequence, a counterbalance on the factor of curvature radius was achieved. The stimuli were provided as defined in each experiment. We measured

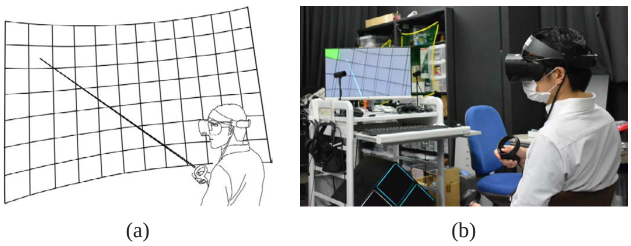


Fig. 2 Interactive Surface: (a) Concept (b) Photograph of Experimental Setting.

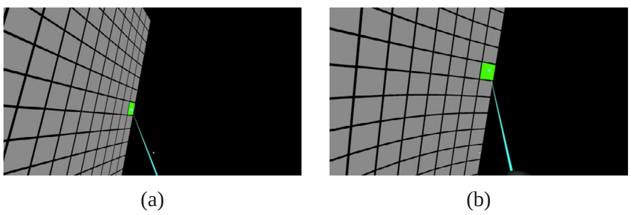
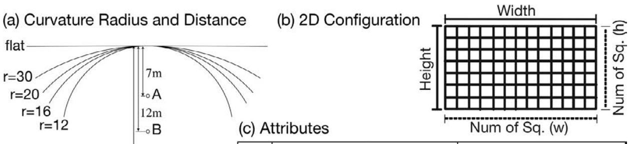


Fig. 3 Participant's Perspective of Marginal Areas on the Interactive Surface: (a) Flat screen (b) Curved screen. The green target is the selective target.



(c) Attributes

	Attribute	Possible Values
1	Distance of viewpoint [m]	A=7, B=12, C=20
2	Curvature radius [m]	12, 16, 20, 30, flat
3	Width x height [m]	35 × 20, 53 × 30
4	Grid number [num of sq.]	5 × 3, 13 × 7, 27 × 15

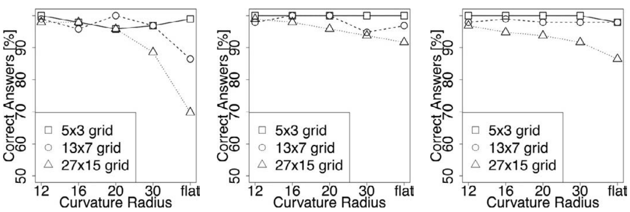
Fig. 4 Surface Conditions for Experiments. (a) Curvature radii and distance are presented in all combinations. (b) The number of squares, width, and height vary as shown in the table (c).

the time from the appearance of the stimulus until the participant pressed the trigger button. If a participant pressed the trigger button while aiming the ray at a wrong square, we counted it as an error.

3.1. Experiment 1: Target Pointing without Search

The target squares repeatedly appeared at three fixed locations (left end, right end, and center as a reset position) of the center row. In this experiment, we measured the basic sensorimotor response for raycasting on a virtual surface. There were 540 trials (90 surface conditions × 6 stimuli without centers) for each participant.

Fig. 5 shows the plots of the percentage of correct answers vs. curvature radius (r), and Table 2 shows the error ratios of Experiment 1. The larger the radius of the curvature, the larger the error ratio. For small squares (27 × 15 grid), the worst percentage of correct answers was 70% when the flat surface was operated from viewpoint A. This percentage could be improved to 98% using curved conditions (r = 12 or 16), which was an improvement of 28%. One reason for this is that the squares contain large perspective distortions in the edges when a flat screen is used (Fig. 3).



(a) Viewpoint A (d = 7 m) (b) Viewpoint B (d = 12 m) (c) Viewpoint C (d = 20 m)

Fig. 5 Percentage of Correct Answers in Experiment 1

Table 1 Speedup by Curved Surface (27 × 15 grid)

Viewpoint	Time by Curved Surface [sec]	Time by Flat Surface [sec]	Speedup Measured [%]	Speedup Predicted [%]
A	1.05 ± 0.24 (r = 20)	1.20 ± 0.47	12.8*	33.6
B	0.95 ± 0.18 (r = 16)	1.00 ± 0.30	4.9	23.7
C	0.87 ± 0.20 (r = 16)	1.02 ± 0.46	14.6*	14.0

a ± *b* denotes that *a* is a mean and *b* is a standard deviation.
*denotes that it is significant at 5% level of significance by T-test.

Table 2 Average Error Ratios Obtained in Experiments 1 and 2 [%]

	r = 12	r = 16	r = 20	r = 30	flat
Experiment 1 (without Search)	1.2	1.8	2.3	4.3	8.2
Experiment 2 (with Search)	3.7	5.0	5.1	5.5	5.7

For the response time, the curvature radii of the shortest operation time were 20 (A), 16 (B), and 16 (C) for the smallest target size. We summarize the speedup from the flat surface along with the predicted speedup obtained by Fitts's law (S^*_c) in Table 1. Using a t-test, we confirmed that curved surfaces enable speedup in pointing operations. Fitts' law fitted well with the measured data from viewpoint C. Although the learning effect was included in the result by repeated actions, it is considered that the effect occurred on all factors equally, and we can regard the observed tendency as reliable.

3.2. Experiment 2: Target Pointing with Search

This experiment incorporates a target-seeking factor in addition to Experiment 1 to prevent the user from remembering the location of the target. For each surface condition, participants had to point to three targets. A target appeared in a position from a position sequence at a time, generated randomly for each surface condition, and was common among all participants. There were 270 trials (90 surface conditions × 3 stimuli) for each participant. No reset was given in this experiment.

Table 2 lists the average error ratios in Experiment 2. The larger the radius of curvature, the larger the error ratio. This trend is consistent with that observed in Experiment 1.

As for the response time, the observed trends were different from those observed in Experiment 1. Although we omitted the details here, the flat condition was the fastest. There are two possible reasons: (a) the effect of seeking time for out-of-sight targets is large, and (b) difficulty varies between factors because each position sequence is generated randomly and short. In the next step, we need to improve the experiments carefully to address these issues.

4 Application: Immersive Photo Browser

The number of photos has been astronomically increasing with the introduction of modern technologies such as mobile devices, cloud photo storage, and high-speed continuous shooting. It is extremely difficult to search for and view photos because of this increase. Virtual reality (VR) can address this issue by providing portable large-screen environments.

Based on the evaluation experiment in the previous section, we designed and implemented a prototype immersive photo browser. It is a suitable application for curved raycasting-based interactive surfaces because it provides a large display with quick and accurate operations.

We developed this application using Unity 2018. The users experienced this VR application using Oculus Rift S as the display and two Oculus Touch controllers as the gesture controllers. Representative features are described in this section.

4.1. Thumbnail Wall

A thumbnail wall is the basis of an immersive photo browser and is used to view a large number of photos simultaneously. We designed and employed a curved surface for the thumbnail wall based on the evaluation experiment described in Section 3. Users select photos of the thumbnail wall for various operations.

Fig. 6 shows an example of a thumbnail wall. Thumbnails at the edge of the wall can be observed to be of sufficient size because they include less perspective distortion with the advantage of a curved surface.

Users can move anywhere in this VE. Continuous navigation (i.e., a user continuously moving in a space) is intuitive, but it easily induces VR sickness. Continuous zooming operations, which are popular in smartphones, also induce VR sickness when used in VR environments.

Therefore, warp-type navigation (i.e., a user moving to a location in a discontinuous manner) should be the primary navigation method coupled with continuous navigation to smoothly adjust the viewpoint of the user.

In the warp-type navigation of an immersive photo browser, users can move to the front of a specified photo by pointing and pressing buttons with the right Oculus Touch controller. Fig. 7 illustrates the scene after moving to the front of the specified photo. For continuous navigation, users can move freely using the left Oculus Touch controller.

Fig. 6 Thumbnail Wall: A total of 1500 photos can be arranged on a wall. A user can view the whole wall naturally as they turn their head.

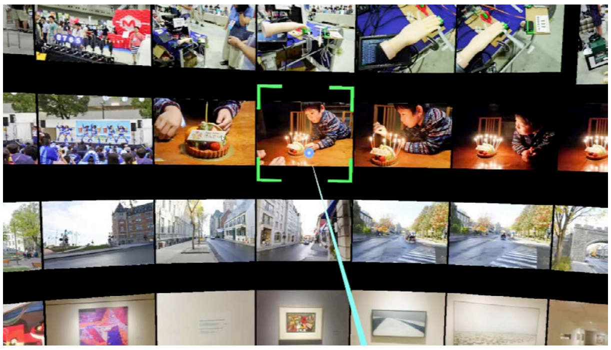


Fig. 7 View after Warping to the Front of a Selected Photo. Green lines show a selection and the cyan line is a ray extended from the user's hand.

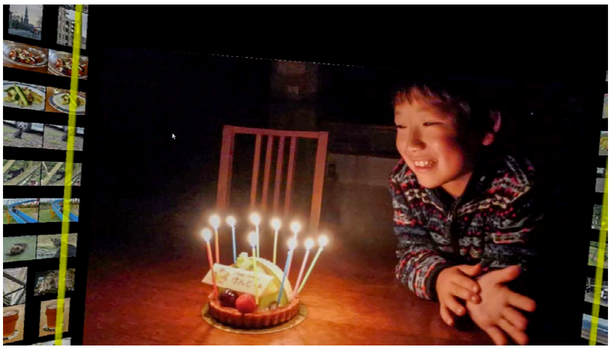


Fig. 8 Photo Panel. Photos can be looked at closely in the immersive environment. A user can move photos freely and compare them in the space.

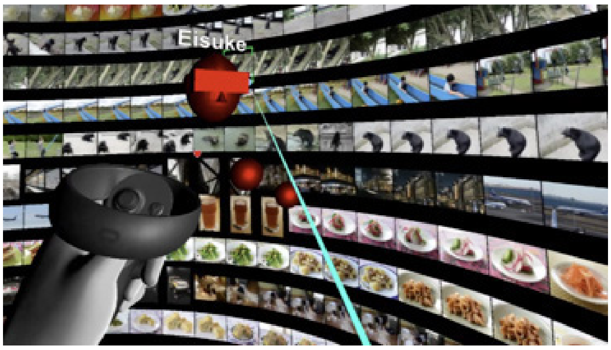


Fig. 9 Collaboration in the Immersive Photo Browser. The avatar of another user can be seen from the viewpoint of the user.

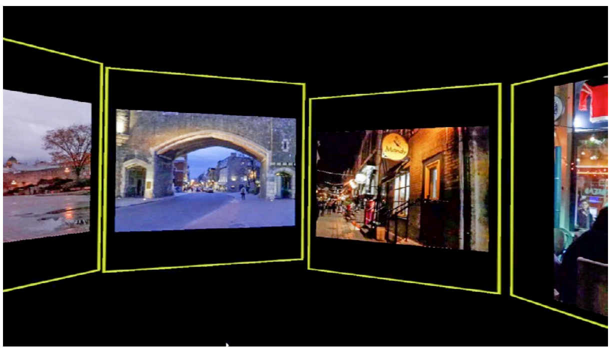


Fig. 10 Virtual Gallery in the Immersive Photo Browser. The photos were selected by pointing to the thumbnail wall and the layout can be adjusted freely.

4.2. Other Features

By pointing at a photo on the thumbnail wall and pressing the trigger button, users can closely view the photo (Fig. 8). Users can quickly move and resize a photo using an Oculus Touch controller.

Fig. 9 shows a scene in which a user collaborates with another user. This collaboration facility is useful in photo-related workflows, such as photo selection for magazine editing, photo galleries, and lectures. Users can also communicate using text chatting and voice chats.

Users can locate photos anywhere they desire to hold personal exhibitions in a virtual gallery (Fig. 10). In addition, users can invite their friends to this gallery.

Among all these features, pointing operations on a thumbnail wall are crucial and a curved interactive surface is considered significantly effective.

5 Conclusion

In this study, we designed experiments to evaluate raycasting-based interactive surfaces and measured the percentage of correct answers and the operation time when surface factors were changed in a VE. The results showed that in the curved surface condition, the percentage of correct answers improved in basic and realistic situations, and the operation time was shortened in situations without target-seeking activities.

These findings can be applied to two-dimensional-style applications, such as photo browsers and GIS. For future work, an experiment should be conducted to clarify the effect of out-of-sight target seeking and normalize the difficulty of the target-seeking task.

References

[1] A. Endert, L. Bradel, J. Zeitz, C. Andrews, and C. North, "Designing large high-resolution display workspaces," in *Proceedings of the International Working Conference on Advanced Visual Interfaces*, AVI '12, pp. 58–65. Association for Computing Machinery, New York, NY, USA, 2012. doi: 10.1145/2254556.2254570

[2] B. Gao, B. Kim, J. I. Kim, and H. Kim, "Amphitheater Layout with Egocentric Distance-Based Item Sizing and Landmarks for Browsing in Virtual Reality," in *International Journal of Human–Computer Interaction*, 35(10), 2018. doi: 10.1080/10447318.2018.1498654

[3] J. Liu, A. Prouzeau, B. Ens, and T. Dwyer, "Design and evaluation of interactive small multiples data visualisation in immersive spaces," in *2020 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*, pp. 588–597, 2020. doi: 10.1109/VR46266.2020.00081

[4] L. Shupp, R. Ball, B. Yost, J. Booker, and C. North, "Evaluation of viewport size and curvature of large, high-resolution displays," in *Proceedings of Graphics Interface 2006*, GI '06, pp. 123–130. Canadian Information Processing Society, CAN, 2006.

[5] T. Takashina, M. Ito, H. Nagaura, and E. Wakabayashi, "Evaluation of Curved Raycasting-based Interactive Surfaces in Virtual Environments," in *2021 IEEE Conference on Virtual Reality and 3D User Interfaces Abstracts and Workshops (VRW)*, 2021, pp. 534–535, doi: 10.1109/VRW52623.2021.00149

[6] C. Wingrave and D. A. Bowman, "Baseline factors for raycasting selection," in *Proceedings of Virtual Reality International*, p. 10 pgs, 2005.

高階知巳　Tomomi TAKASHINA
映像ソリューション推進室
Imaging Solution Development Department

伊藤　充　Mitsuru ITO
映像ソリューション推進室
Imaging Solution Development Department

長浦　仁　Hitoshi NAGAURA
株式会社ニコンシステム
Nikon Systems Inc.

若林英佑　Eisuke WAKABAYASHI
株式会社ニコンシステム
Nikon Systems Inc.

高階知巳
Tomomi TAKASHINA

長浦　仁
Hitoshi NAGAURA

若林英佑
Eisuke WAKABAYASHI