ScreenX: Public Immersive Theatres with Uniform Movie Viewing Experiences

Jungjin Lee, Sangwoo Lee, Younghui Kim, and Junyong Noh

Abstract—This paper introduces ScreenX, which is a novel movie viewing platform that enables ordinary movie theatres to become multi-projection movie theatres. This enables the general public to enjoy immersive viewing experiences. The left and right side walls are used to form surrounding screens. This surrounding display environment delivers a strong sense of immersion in general movie viewing. However, naïve display of the content on the side walls results in the appearance of distorted images according to the location of the viewer. In addition, the different dimensions in width, height, and depth among theatres may lead to different viewing experiences. Therefore, for successful deployment of this novel platform, an approach to providing similar movie viewing experiences across target theatres is presented. The proposed image representation model ensures minimum average distortion of the images displayed on the side walls when viewed from different locations. Furthermore, the proposed model assists with determining the appropriate variation of the content according to the diverse viewing environments of different theatres. The theatre suitability estimation method excludes outlier theatres that have extraordinary dimensions. In addition, the content production guidelines indicate appropriate regions to place scene elements for the side wall, depending on their importance. The experiments demonstrate that the proposed method improves the movie viewing experiences in ScreenX theatres. Finally, ScreenX and the proposed techniques are discussed with regard to various aspects and the research issues that are relevant to this movie viewing platform are summarized.

Index Terms—Multi-projection, immersive display system, image representation, immersive theatres

1 Introduction

Over the past few decades, researchers in computer graphics have strived to provide people with more visually immersive experiences than previously possible. For example, the continual technical advances in the various research fields of 3D graphics applied to movies have successfully satisfied the ever-growing expectations of the audience, which has been seen with recent releases of visually stunning blockbuster movies and lifelike animated films. In particular, the visual domain has been expanded from flat 2D screens to 3D spaces using stereoscopy. The depth perception produced by stereoscopy effectively brings the audience one step closer to the 3D virtual world provided by more realistic visual content.

Multi-projection techniques allow the display of images or video content on any extended area. This alternative display setup leads to interesting immersive experiences for the audience. For example, the content displayed on the surrounding screens can deliver a strong sense of immersion. This idea was first introduced through a demonstration of CAVE [1] and its variations have since been used in numerous different applications in tandem with the advancement of digital projection technology. These applications have served commercial, business, education, and entertainment purposes. However, the multi-projection technique has been primarily showcased at short term events such as exhibitions at international expos or at relatively expensive special venues such as theme park rides.

The proposed novel platform, ScreenX, which is an abbreviation of Screen Experience, is a system that enables ordinary movie theatres to be multi-projection ready. ScreenX utilizes the left and right side walls as additional projection areas and projects ScreenX-enabled content such as movies and commercials onto these walls (Fig. 1). In the design of the ScreenX system, specific constraints were imposed by movie theatre chains.[1] First, the cost of installation should be minimal for wide deployment of the system. Second, the original atmosphere of the movie theatre should be preserved. Consequently, major modifications of the current structures of the theatres were not allowed; the only change that was allowed was the installation of a small number of inexpensive projectors. This differentiates ScreenX from similar alternatives such as IMAX [2] and Cinerama [3], both of which require special screens in a modified environment. ScreenX also differs from the recently introduced IllumiRoom [4] in that their system is targeted for spaces with significantly smaller scales than movie theaters provide.

For the moviegoer, there are preferred seats in a theatre because the perceived content quality might vary based on the seating position, particularly those along the sides. Similarly, the stereo effects might be diminished from these positions. Unfortunately, the ScreenX environment exacerbates this situation. First, the naïve display of a ScreenX-enabled movie on the surrounding walls will result in distorted images depending on the location of the viewer. This

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1. This was an official request by CJ-CGV, which is the largest movie theatre chain in Korea.

Fig. 1. The ScreenX system converts ordinary movie theatres into public immersive theatres through utilizing the left and right side walls as additional screens using a multi-projection technique without modification of the existing theatre structure.

distortion can severely interfere with the sense of immersion that comes from the surrounding displays. Second, each movie theatre has different dimensions in width, height, and depth. This might lead to different viewing experiences by the audience according to the theatre. For example, a portion of the side image may be visible in one theatre while not visible in another. Furthermore, for movie theatres with extraordinary dimensions in one direction, it could be better to exclude them as outliers than to exhibit somewhat different image content to the audience in those theatres. Consequently, for successful deployment of this novel movie viewing environment, it is important to minimize the seat-dependent image distortion and to provide uniform viewing experiences regardless of the choice of theatre.

The proposed strategy to overcome these problems can be summarized as follows. First, an image representation model is proposed that is created for each viewpoint in the theatre. The creation of the image representation model entails sampling of the viewing directions horizontally and vertically, followed by projection of the results on the side walls. Minimizing the differences between the representations created for each viewpoint leads to the minimum average distortion experienced by the entire audience. Second, the theatre suitability criterion estimates and evaluates the suitability of each theatre for the ScreenX system. This estimation is performed through comparing the image representation of each theatre with the standard image representation, which is obtained through analyzing the collection of all seats from all theatres in the database. The estimation effectively identifies outlier theatres. The elimination of outlier theatres allows similar viewing experiences under the diverse dimensions and configurations of various movie theatres. Third, the proposed content production guidelines help place scene elements in appropriate regions on the side walls of the chosen theatres according to their importance. The important elements should be placed on areas that are visible from all chosen theatres, while less important secondary effects can be safely placed on areas visible in only a subset of the theatres.

One of the significant issues that the graphics and virtual reality (VR) communities have not thoroughly investigated is how to generate reasonable multi-viewer solutions from single viewer content. There has been no clear formalization or measurable metric that can assist in automating this process, despite the recent efforts in the effective generation of view interpolation [5] and stereo content [6], [7]. Consequently, the production of the content required in a multi-viewer environment, with one example being multi-viewer rides, often uses a considerable amount of manual intervention. The creation of ScreenX content poses a similar problem because the content displayed on the side screens must be viewed from different seats, which results in non-uniform viewing experiences. This study can be considered the first attempt to design and evaluate a generalized framework for this situation. The primary contributions of this study are summarized as follows:

- A multi-projection system that can be applied to ordinary movie theatres is introduced. This effort brings immersive viewing experiences one step closer to reality in daily life.
- A novel image representation model is proposed that ensures the minimum average perspective distortion of the content displayed on the side walls. This leads to uniform movie viewing experiences regardless of the seating locations in a theatre. An effective method of culling outlier theatres is also proposed.
- The proposed metrics are evaluated using various user studies to justify the formalization. The proposed formalization is the first attempt to provide an automated multi-viewer solution for single viewer content.

This paper opens numerous research possibilities related to this new movie viewing platform. The specific constraints associated with this unique environment require additional studies to further improve the immersive viewing experiences.

2 Related Work

Immersive display system. Many researchers have attempted to enhance visual experiences over the past few decades. The introduction of a room-sized immersive space created by CAVE [1] denoted the beginning of spatially immersive display research. After its pioneering demonstration, many variants have been presented. For example, Raskar presented a display system that projects visual content onto a single surface using multiple projectors [8]. Similarly, i-Cone is a panoramic display that combines with a multi-projection system [9]; omnistereo display systems [10] extended i-Cone using stereoscopic techniques. Meanwhile, there have been several studies that focus on expanding the boundaries of the screen. Baudisch et al. [11] produced a high resolution display with a combination of low resolution projectors in order to generate an overview of the content that also presents the details. Surround Video [12] and the IllumiRoom prototype [4] overcame screen dependency through projecting visual content onto an extended environment. There have also been studies that focused on generating an immersive feeling through the use of peripheral vision [13], [14]. Avraham and Schechner [15] introduced an extrapolation method that creates the peripheral view from the existing content.

Multi-projector calibration. Performing geometric calibration for multiple projectors and blending their projection images are essential prerequisites for creating a seamless multi-projection display that the ScreenX system builds on. The use of cameras can automate this process as well as automate the possible follow-up maintenance. Raskar et al. [16] and Zhoua et al. [17] utilized stereo vision to determine the display surface geometry and the intrinsic and extrinsic parameters of the individual projector. PixelFlex [18] and Bhasker et al. [19] computed the homography of each projector through observing the patterns projected through a camera. Sajadi and Majumder proposed a set of methods [20], [21] that can help register multiple projectors on a curved surface using a single uncalibrated camera under surface-specific assumptions. However, these methods only work well on regular screens without obstacles. RoomAlive [22] automatically builds a multi-projection system in a furnished room using a combination of a projector and a depth camera. However, the immediate application of this system to ordinary movie theatres is difficult due to limitations in the range and resolution of the depth sensor. As is elaborated in the discussion section, there are important open issues in building high quality multi-projection systems for existing theatres. Instead of attempting to solve these issues in this paper, manual calibration is relied upon, which is similar to the currently available commercial software [23], [24].

Immersive content production. With the development of immersive display systems, studies that focus on the production of appropriate content have also been conducted. Panoramic video is a representative form of immersive content, and it requires different (and typically more elaborate) approaches compared with the creation of its general 2D counterpart. For example, studies [25], [26], [27] that consider the creation of video panoramas employ multiple synchronized video cameras to acquire horizontally elongated scenes. Efficient methods of producing stereoscopic content in the domain of panoramic images or videos also have been proposed. For example, image-based stereo panoramas have been generated through rotating stereo cameras [28], [29]. Peleg et al. [30] proposed a method to create a concentric panorama, that captures the stereo panoramic images of moving scenes. The omni-stereo multi-camera system [31] allows the creation of a panoramic stereo video with a high resolution and quality. These studies are similar to this one in that the common goal is to provide immersive experiences to the audience. However, this study differs because the focus is on providing optimal and similar experiences regardless of the position of the viewer and the choice of theatre.

Image space optimization. Image space optimization is widely used in the field of computer graphics and vision. Igarashi et al. [32] presented a user controllable deformation technique for 2D shape manipulation that minimizes the distortion of the local shape. Methods based on warping have been used for various image and video applications, including video stabilization [33], optimizing image content [34], and perspective manipulation [35]. Vangorp et al. [36] provided guidelines for street-level image-based renderings using a perceptual model based on acceptable perspective distortions. The similar problem of perspective distortions depending on viewpoints is addressed in this study in the context of multi-viewer scenarios in theatres. The proposed image representation model is designed to minimize the average perspective distortion of the images displayed on the side walls of a theatre in this situation. The images displayed on the side walls are manipulated using a method similar to the abovementioned optimization techniques. However, the proposed optimization is based on Laplacian coordinates and formulates a metric for local shape distortions.

Media retargeting. Media retargeting is a research field that is specialized in adjusting the input visual content to appropriately fit a target display. Video resizing is a typical example of a media retargeting technique. Many recent studies have relied on optimization techniques to ensure the preservation of important regions when content is retargeted to a restricted display. The application of cropping or panning removes unimportant visual elements [37], [38]. Seam carving [39], [40] achieves a similar goal of removing unimportant regions through effective seam blending. Image warping [41], [42], [43] deforms images non-homogeneously. Video retargeting systems [44], [45], [46], [47] also focus on improving the temporal coherence for motion. Retargeting techniques are also used to manipulate stereoscopic content. Lang et al. [6] presented a nonlinear disparity mapping system based on warping using a set of disparity mapping operators. A content-aware disparity retargeting method was introduced by Chang et al. [48] in order to consider different viewing environments for stereoscopic content. Yan et al. [49] proposed a depth mapping method for stereoscopic videos that preserves the original video quality. The stereoscopic effect can be maintained through disparity retargeting after changing viewing environments. The proposed approach also aims to provide the audience with uniform immersive experiences through performing target theatre specific content retargeting.

3 SCREENX INSTALLATION

A movie theatre consists of the front screen and the left and right walls, as well as the back wall. Because the proposed system utilizes the left and right walls as additional screens, the left wall is used as the left logical screen and the right wall as the right logical screen.[2] Multiple projectors form each of these two logical screens. In order to determine the

2. A logical screen refers to mean a display region defined on any physical surface.

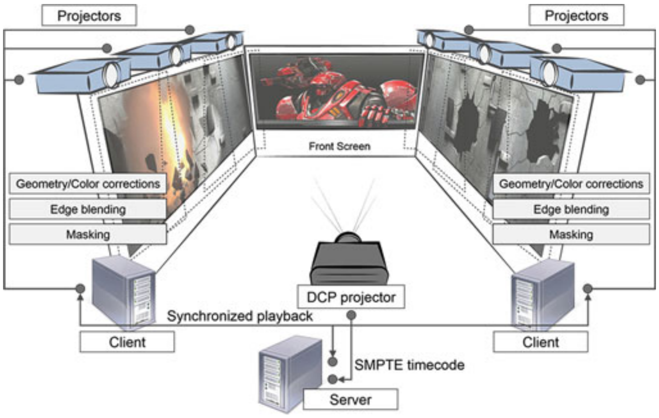

Fig. 2. A setup of the ScreenX system.

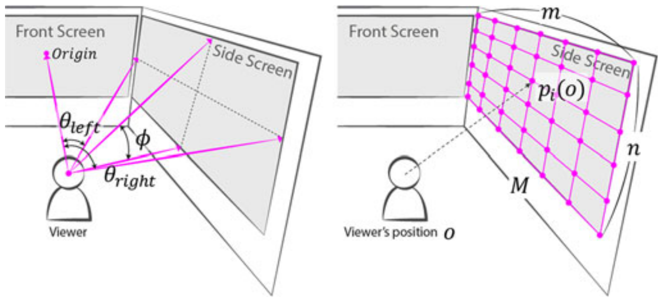

Fig. 3. A visualization of the notations used to create the image representation model. Note that the above illustrations only depict for the right screen for brevity. The same depictions apply to the left side screen.

relationship between the projectors and align them to create a perfect logical screen, a planar perspective transform (i.e., homography) for each projector is estimated semi-automatically [16]. Non-linear edge blending is used in order to obtain seamless transitions between the images created by adjacent projectors. Similarly, black offsets between the projectors are matched and color/geometry corrections are performed in order to ensure consistent image qualities [18]. A black mask is applied to the top and bottom areas, which are outside the horizontal extension of the front screen, in order to match the heights between the front and side logical screens. Low projection areas where seats are affected are also masked out in order to avoid possible interference of the beam with the viewer's eyes. The synchronization of the multiple projectors is managed using TCP/IP sockets in a client-server network. While the main movie is projected onto the front screen using the main digital cinema projector (DCP), the left and right logical screens project additional visual content that is synchronized with the main projector using a time code defined by the Society of Motion Picture and Television Engineers. Fig. 2 illustrates a typical setup of the proposed system. Note that these steps do not require modification of the theatre structure, other than the installation of the additional projectors, or alteration of the main projection system. Simple deactivation of the additional projectors reverts the system to the original movie playing mechanism. For brevity, the side logical screen is referred to as the side screen in the following sections, although the side walls are not equipped with physical silver screens.

4 Image Representation Model

The proposed image representation model ensures the minimum average distortion of the images displayed on the side screens when they are viewed from various seat positions in a theatre. This provides similar movie viewing experiences regardless of the seating locations in the theatre. In order to formulate a uniform movie viewing experience as a mathematical model, the viewing directions are sampled from each viewer's position to the side screens horizontally and vertically with a uniform angle. Each sampling point can be represented in the 2D polar coordinate space $S \subset (\theta, \phi)$, where θ and ϕ represent the horizontal and vertical coordinates of the point, respectively. The origin of S is located at the center of the front screen. The range of the horizontal angles that cover the side screens is defined as follows:

$$\theta_{\text{left}} \leq \theta_{\text{u}} \leq \theta_{\text{right}}, \tag{1}$$

where θ_{left} and θ_{right} denote the horizontal angle that spans the side screens in the left and right directions, respectively. For each horizontal angle θ_{u}, the range of the vertical angles is defined as follows:

$$\phi_{\text{u,top}} \leq \phi_{\text{v}} \leq \phi_{\text{u,bottom}}, \tag{2}$$

where $\phi_{\text{u,top}}$ and $\phi_{\text{u,bottom}}$ correspond to the vertical angle for the top and bottom boundaries of the side screen for the horizontal angle θ_{u}, respectively. This setup results in the range of vertical angles varying according to the distance from the viewer to the side screen. Uniform sampling of m horizontal angles in the range of θ_{u} followed by uniform sampling of n vertical angles in the range of ϕ_{v} for each horizontal angle produces a grid mesh M which is defined in the image space $I \subset (u, v)$ overlaid on the side screens. In this paper, m = 30 and n = 10; these values were determined empirically and worked well for all experiments. Fig. 3 visualizes the setup of the proposed method. The position of ith vertex $p_i \in (u, v)$ of M on the image space I varies according to the viewer's three-dimensional position o. Therefore, the image coordinates $p_i(o)$ of M on the side screen also vary accordingly. This implies that $p_i(o)$ created from the position o will appear distorted from a different position, o', because the positions have different image representation models. Fig. 4 presents an example of the different appearances of M corresponding to different seat positions.

In order to compute the final grid mesh $\hat{M}$ that will lead to the minimum distortion in the image space, a reference mesh M_{ref} is used to start. M_{ref} corresponds to the mesh created from a reference viewpoint. A reasonable candidate for the reference viewpoint is the camera location used for the generation of the side content. In general, however, this location is difficult to obtain from filming sites, while it is easy to obtain from the computer graphics content. If this position is unavailable, an alternative position is selected and obtained as follows. First, the content for the side screen is resized to match the height of the front screen; this is performed in the calibration stage. Second, the reference viewpoint is the center position of the resized content, whose third coordinate is determined as the center of the theatre width. The magenta circle in Fig. 5 indicates the reference viewpoint.

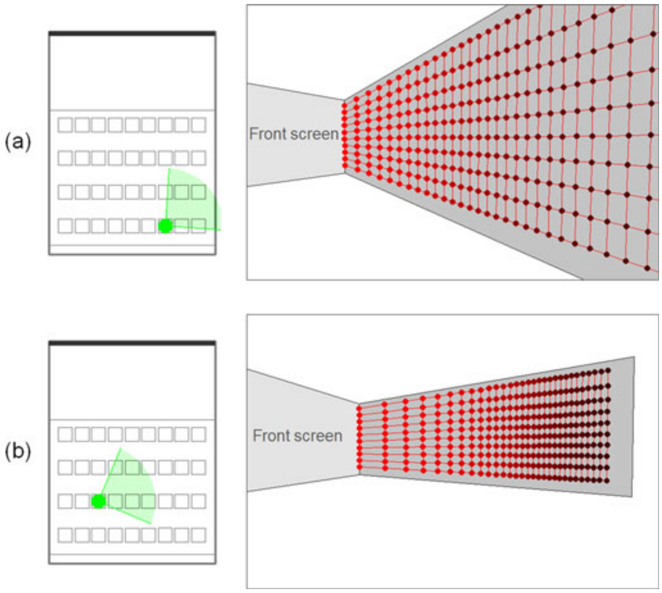

Fig. 4. The image representation of M from the viewpoint of (a) appears distorted from different seat positions (e.g., (b)). The left column presents the viewpoint of the right column. The intensity of the red vertices reflects the value of the weight w in Equation (4).

Laplacian coordinates have been successfully used to represent the local shape around the vertex of a mesh in the field of geometry processing [50], [51], [52]. In the same manner, Laplacian coordinates are used to measure the distortions of $p_i(o)$ in the proposed method. The local shape around a vertex p_i can be described using Laplacian coordinates δ_i, as follows:

$$\delta_i(o) = p_i(o) - \frac{1}{n_j} \sum_{j \in N_i} p_j(o), \tag{3}$$

where N_i denotes the neighbor vertices of p_i, and n_j is the cardinality of N_i. The weight $w_{i,k}$ is defined as an exponential falloff away from the center of the front screen (Equation (6)). The final local shape $\hat{\delta}_i$ is defined as follows:

$$\arg\min_{\hat{\delta}_i} \sum_k \sum_i w_{i,k} (\hat{\delta}_i - \delta_i(o_k))^2 \tag{4}$$

subject to

$$\begin{cases} \hat{p}_u^* = u^* \\ \hat{p}_v^* = v^* \end{cases} \textit{and } \hat{p}^l = c^l, \tag{5}$$

where o_k represents the kth seat position. Each condition in Equation (5) indicates the boundary and line constraints, respectively. For $\hat{p}$ satisfying $\hat{\delta}_i$, $\hat{p}^*$ is the set of boundary vertices of $\hat{p}$. u^* and v^* represent the boundary values of the u and v axes, respectively. $\hat{p}^l$ and c^l are the v values of the vertices of $\hat{M}$ and M_{ref}, respectively, which are connected to the front screen. The line constraint ensures continuity between the front and side screens. The weight $w_{i,k}$ considers the viewer's attention and is defined as follows:

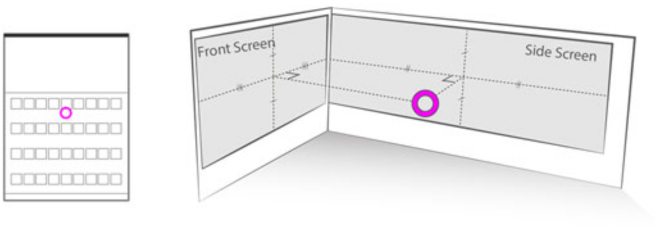

Fig. 5. A visualization of the reference viewpoint.

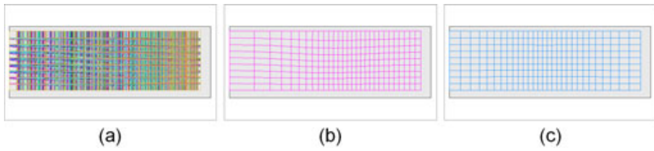

Fig. 6. For the right screen: (a) a visualization of all meshes created from all seat positions in the theatre; (b) the image representation of $\hat{M}$; (c) the image representation of M_{ref}. $\hat{M}$ tends to be warped backward in relation to M_{ref} because the seats are primarily placed behind the reference viewpoint indicated in Fig. 5.

$$w_{i,k} = e^{-\frac{(\frac{\theta}{\pi})^2}{\sigma^2}}. \tag{6}$$

The falloff reflects the assumption that viewers tend to focus on the front screen and the likelihood of looking at the side screens far from the front screen diminishes smoothly. $\theta = 0$ indicates that the viewer looks at the center of the front screen. $\theta = \pi$ indicates that the viewer looks toward the back of the theatre. The variance σ reflects the viewer's viewing angle. In the experiments in this paper, $\sigma = 0.5$ was set. $\hat{M}$ with minimum distortion of local shapes when observed from all viewpoints can be computed using $\hat{\delta}$ and $\hat{p}$. $\hat{p}$ indicates the positions of p for the corresponding $\hat{\delta}$. This problem can be formulated as a Poisson equation, as follows:

$$\Delta \hat{p} = \hat{\delta}. \tag{7}$$

The unknown variable $\hat{p}$ can be obtained through applying a single linear system solver. Deforming M_{ref} to $\hat{M}$ produces the final optimized content for the side screen. Fig. 6a illustrates all meshes created from all seat positions overlaid on the side screen. Figs. 6b and 6c present the image representation of $\hat{M}$ and M_{ref}, respectively. Fig. 7 illustrates the result of the proposed method.

Note that the Laplacian coordinates in Equation (3) can be replaced with other metrics for local shape distortions.

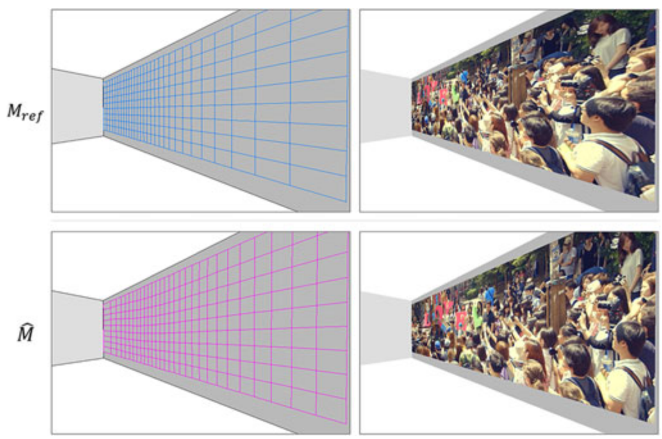

Fig. 7. The first row is the image representation of M_{ref} and the input content. The second row is the image representation of $\hat{M}$ and the output content. The content of $\hat{M}$ is deformed in favor of the seats located in the back.

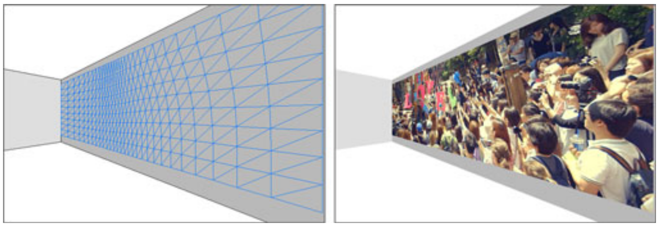

Fig. 8. The result from the optimization with the similarity transformation term. First, each grid cell is split into two triangles and the similarity transformation term is applied instead of Equation (3).

The similarity transformation term that measures the deviation of a triangle under a similarity transformation has been successfully used in various applications [32], [33], [53] in which the local shapes of the input content should be preserved. Fig. 8 presents the final mesh and content produced after the optimization using the similarity transformation term introduced in Chaurasia et al. [53] in place of Equation (3). The vertices of the resulting mesh are poorly distributed and the vertical bending is noticeable. As a result, the perspective distortions are not appropriately reduced in the output content. The unsatisfactory outcome produced using the similarity transformation results from its inability to describe the motion between the perspective distortions arising from different seat positions. This experiment verifies that the Laplacian coordinates are a more suitable choice for the proposed optimization than the state-of-the-art alternatives.

5 Theatre Suitability Estimation

Visual experiences may differ due to the nature of the surrounding display observed in the diverse dimensions and configurations of different movie theatres. Depending on the degree of such variations, it is possible that a large portion of the content prepared for the side screens will not be visible in theatres with somewhat non-standard structures. In this case, it is desirable to exclude outlier theatres that have extreme variations. Therefore, a mechanism is provided that measures how each theatre fits the ScreenX system. Thus, unsuitable theatres can be identified and eliminated from the group of candidates for installation of the ScreenX system.

The image representation model explained in Section 4 also measures the theatre suitability. Fig. 9a presents the location of all seats from all candidate theatres after normalization using the width of the front screen. The application of the same method explained in Section 4 produces an image representation $\hat{M}_{total}$ that is optimized for all seats in all theatres. Then, the suitability can be estimated through comparing $\hat{M}_{total}$ with M for each theatre. E_A indicates the error or the degree of unsuitability for theatre A, as follows:

$$E_A = \frac{1}{k} \cdot \sum_k \sum_i w_{i,k} (\hat{\delta}_i^{total} - \delta_i(o_k^A))^2, \tag{8}$$

where o_k^A is the kth seat belonging to theatre A. $\hat{\delta}_i^{total}$ is the ith local shape of $\hat{M}_{total}$. The greater the value of E_A, the less suitable theatre A is. Fig. 9b presents the values of E for all theatres in the database. These values indicate the differences in the seat distribution of each theatre compared with the standard model of $\hat{M}_{total}$. After estimating the E values for all theatres, the outliers are excluded using a threshold value of E_{TH}. The purpose of this outlier removal step is to provide similar viewing experiences in various theatres, as well as to increase the usability/visibility of the side content because each culling enlarges the area that will be visible in all final candidate theatres. The threshold to eliminate the outliers can be determined according to several criteria, and their details are explained in the discussion section.

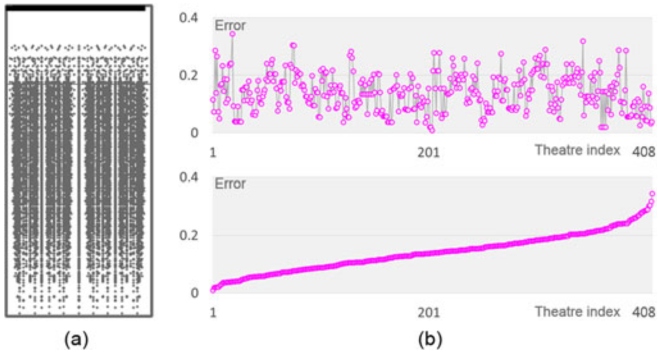

Fig. 9. (a) Plotting of the locations of all seats from all movie theatres in the database; 408 movie theatres were included in this study. The database contains the real measurements from the movie theatres. The gray dots indicate the seat locations and the black bar indicates the front screen. The upper graph of (b) presents the E values of all theatres. The X- and Y-axes denote the theatre index and E value, respectively. Sorting the E value in the upper graph produces the lower graph.

6 Content Production Guideline

It is impractical to optimize the visual content for the side screens for any specific theatre. Similarly, it is undesirable to remove any important visual elements that should be displayed on the side screens according to the choice of the theatre. Therefore, the application of appropriate guidelines in the stage of content production can prevent this problem.

The guidelines uses the 2D polar coordinate space of a viewing angle. The viewing angle image $G_m \subset (\theta, \phi)$ $(-\pi \leq \theta \leq \pi, -\frac{\pi}{2} \leq \phi \leq \frac{\pi}{2})$ represents the side screens of the mth theatre. The label f_n^m of the nth pixel in G_m is defined as follows:

$$f_n^m = \begin{cases} \alpha & if\ \ p_i(O) \in I\ \ and\ \ p_i(O) \notin J \\ \beta & otherwise \end{cases}, \tag{9}$$

where α and β indicate the regions that are available and unavailable for projecting content, respectively. $p_i(O)$ denotes the position projected with perspective from the viewpoint O to the image plane of the side screen. I is the image space within the side screens, and J is the masking region explained in Section 3 for the audience seats $(J \subset I)$. O is located at the average position of all seats. This standard viewpoint is used to normalize the front screen in the polar coordinate space. The seat masking J prevents the beams of the side projectors from going into the eyes of the viewers. Typically, this masking area covers a maximum of one meter above the horizontal or sloped arrangement of the rows of seats, and this area is adjustable. For k theatres, the guideline G_{total} is the viewing angle image for the entire set $\mathrm{N} = \{G_1, G_2, G_3, ..., G_k\}$. Its label f_n^{total} is defined as follows:

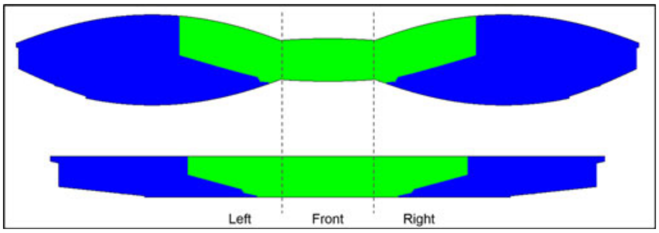

Fig. 10. The upper row is a guide image in the polar coordinate space, while the lower row is the image in the 2D image space. The green, white, and blue indicate α, β and γ, respectively.

$$f_n^{total} = \begin{cases} \alpha & if\ f_n^m{=}\alpha\ for\ all\ \mathrm{N} \\ \beta & if\ f_n^m{=}\beta\ for\ all\ \mathrm{N}\,. \\ \gamma & otherwise \end{cases} \tag{10}$$

The areas with the α label indicate the regions that are visible in all theatres, while the areas with the β label indicate the regions that are not visible in all theatres. The areas with the γ label are visible in some theatres and not visible in others. These guidelines present information regarding which areas can be utilized for the placement of scene elements in the preparation of the content for the side screens. For example, important objects that affect the storyline of a movie should be located in the α region. Less important patterns or effects whose purpose is to merely supplement the main content can be located in any region except β. The guide image based on the polar space can be easily converted to the 2D image space. The producers can choose either space of the guide image according to the rendering method for the content creation. Fig. 10 presents examples of guide images in each space. In this paper, the focus is on managing the placement of the important objects through pre-visualizing the safe regions that will be visible in all theatres. The peripheral visual information can affect the sensation of motion (e.g., it can make a traveling shot feel faster or slower). This provides cinematographers an additional tool but also requires additional guidelines.

Fig. 11. The lab theatre.

7 Results

All experiments were performed in a lab theatre with 32 seats, which was a small replica of an actual movie theatre with additional projectors for the activation of the ScreenX system (Fig. 11). The ScreenX system consists of one master server and two slave clients on a PC with an $Intel\ Core\ i7$ 3.40 GHz CPU with 8 GB memory and a $NVidia\ NVS\ 510$ graphics chipset. Five $Panasonic\ PT-EX500E$ LCD projectors with 5,000 ANSI lumen were installed for each side screen. The proposed retargeting method using the image representation model was also implemented on a PC with the same specifications. It required 16 ms to compute the optimal image representation with a 30×10 grid mesh. Next, the warping of the image representation was performed in real time for a video with a resolution $1{,}024 \times 768$.

To date, a method that can generate physically correct ground truth data with which the results of the proposed system can be compared is not available. Therefore, in order to verify the validity of the proposed method, a diverse set of experiments were conducted. The first experiment compared the output content resulting from the proposed method with the original content. Fig. 12 presents images captured from the viewpoints of three random seats. In the original content, perspective distortions are apparent when viewed from all three seats. In the first and second images, the front areas of both side screens are squeezed whereas the rear areas are stretched. This distortion can interfere with the sense of immersion. The second row demonstrates that the proposed method

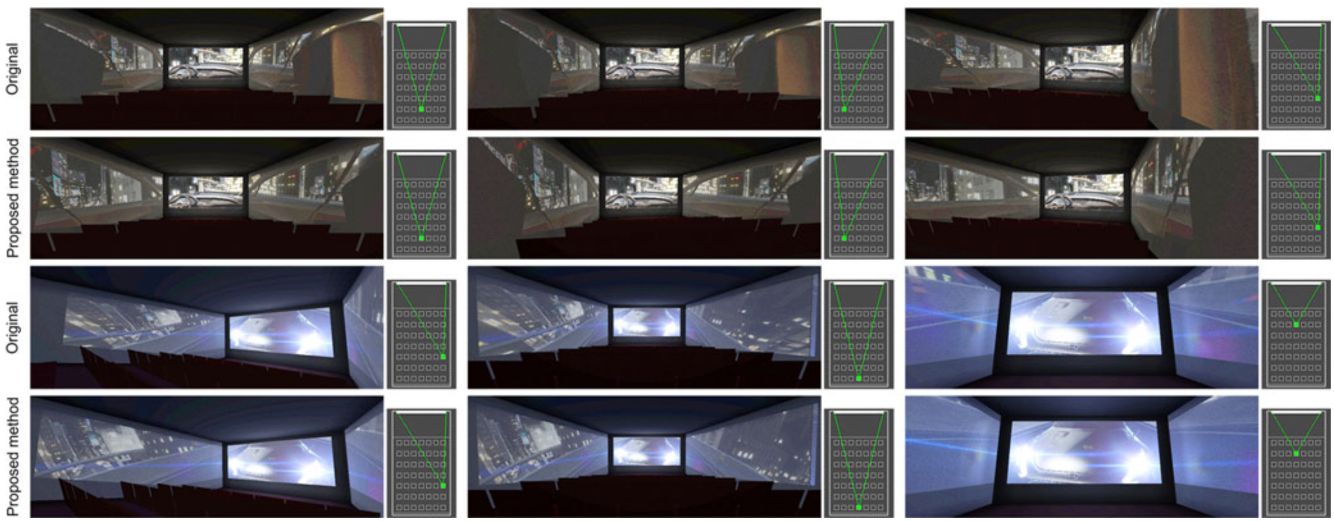

Fig. 12. Comparisons between the original content and the content resulting from the proposed method. Please zoom in for details.

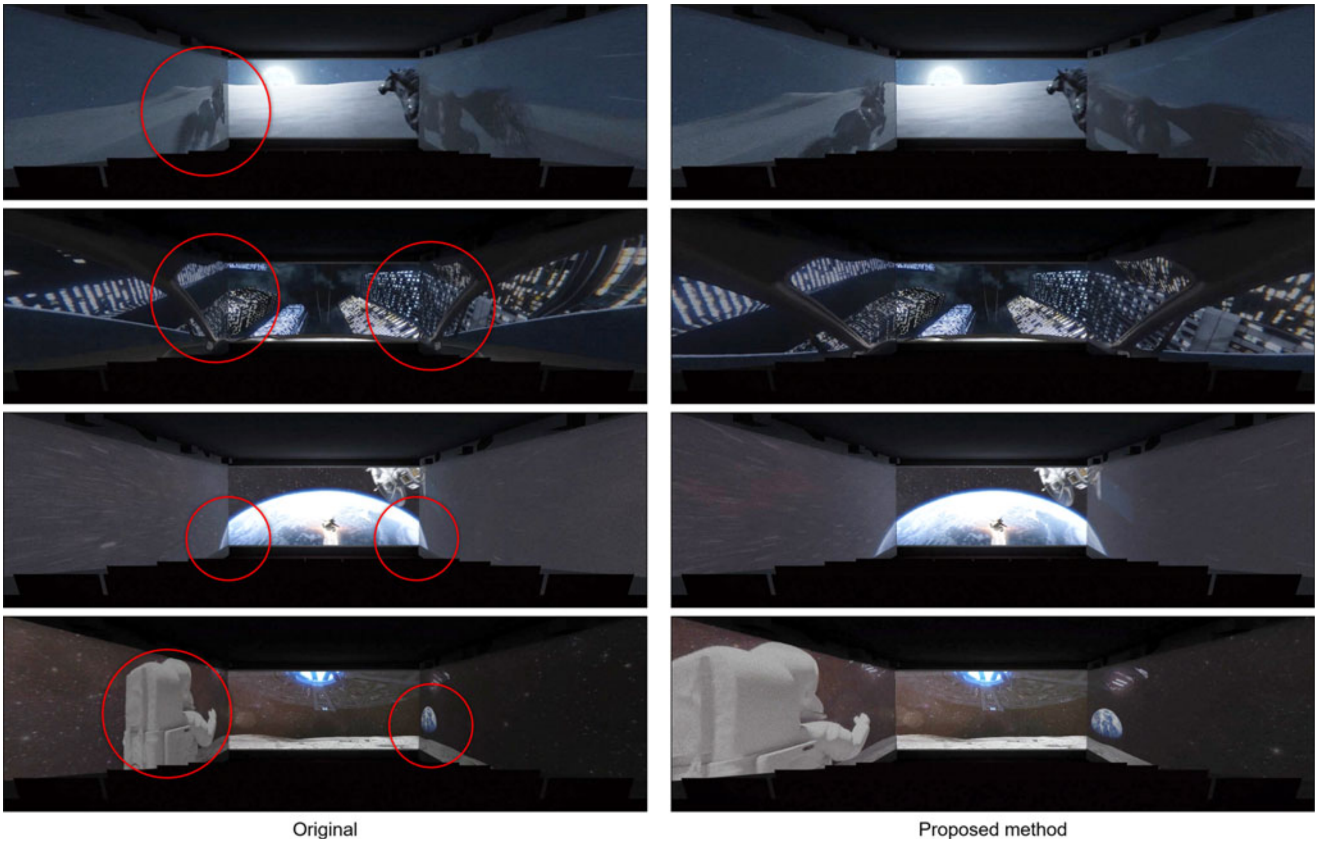

Fig. 13. Comparisons between the original content and the content resulting from the implementation of the proposed method for various scenes.

effectively reduced the distortion and consequently the output content has clearer perspective effects for the three seat locations. The image in the third column illustrates the situation in which the viewer is seated very close to the side screen. The original content displayed on the right screen is difficult to interpret due to the close proximity. In contrast, the proposed method generates a better representation of the content. The third and fourth rows provide another example that illustrates the suitability of the proposed method. The buildings of the original content were severely distorted and the overpass bent downward. The proposed method alleviates these problems and improves the quality of the resulting images. Viewers in the front seats tend to focus on the front screen and the likelihood of turning their heads to watch the side screens is relatively low because the front screen contains the most important scene elements. However, viewers in the back seats can shift their attention from the front to the side, and back to the front screen relatively easily. This observation influenced the weighting scheme described in Equation (6). In particular, a larger value is assigned to the seats with a narrower viewing angle between the front and side screens. Therefore, the optimization is biased for the seats in the back. This explains why, in the lower two images of the third column captured from the viewpoint located in the front, the result from the proposed method has a relatively larger distortion than the original content. Fig. 13 presents additional comparisons for various scenes. In all cases, noticeable perspective distortions (i.e., red circles) are resolved using the proposed method. The resulting image sequences can be found in the accompanying video.

The proposed method improves the visual quality of the content perceived by the viewers situated in different movie theatres. Fig. 14a presents the reference image for the left screen that is observed from the ideal viewpoint. Figs. 14b and 14c present example projections in six different theatres of the content displayed naïvely and using the proposed method, respectively. All images were captured from the viewpoint of the center seat. The front and right areas in the image were removed for better presentation. The observation of the content in 14b reveals that perspective distortions are perceived from the center seat for some theatres, which implies that the viewing experiences can be less optimal according to seat positions in each theatre. For example, in Theatres#3, #4, and #5 in 14b, individuals in the front area are difficult to recognize. In contrast, the results from the proposed method in 14c are less sensitive to these variations. The target theatre-specific content retargeting provides the audience with fewer distorted images regardless of the seat positions, which leads to uniform immersive viewing experiences.

Fig. 15 quantitatively presents the effect of optimizing the content using the image representation model. In order to accurately assess the quality of the deformed content generated using the proposed method, the perspective distortions were measured in a virtually simulated environment using a uniform grid image as the input content. The perspective error for each viewpoint was defined as the variance of the angles between the viewing vectors to the two neighboring cells across the grid. The greater the value of the variance was, the larger the perspective distortion was perceived to be. Fig. 15a presents the comparison between the errors obtained before and after applying the proposed method for all seats in

Fig. 14. Comparisons of example projections of the content displayed naïvely and using the proposed method in six different theatres.

the theatre of Fig. 4. The error values of the original content rapidly increased as the seat locations deviated further from the reference viewpoint. The proposed method effectively suppressed the errors of the back and side seats while retaining small errors in the front seats. Fig. 15b presents the average error of all seats for each theatre in the database. For the original content, the error values were generally high and tended to fluctuate due to the different dimensions of the theatres. In contrast, the proposed method guarantees a low level of perspective errors across all theatres.

One simple method of determining the optimal multi-viewer solution for single viewer content would be to re-project the reference viewpoint of the content onto the center seat. Fig. 16 presents comparisons between the content produced using re-projection and using the proposed method. The re-projected content is obtained through deforming the original content using the image representation model corresponding to the center seat. However, the re-projection of the viewpoint cannot ensure the minimum average distortion of the images when viewed from different locations. For example, Figs. 16b and 16c present the same scene viewed from different locations. As seen in the dotted boxes, the result of the proposed method produces more uniform appearances for the side mirrors and windows in the building than the simple re-projection does between the two different locations. In addition, the continuity between the front and side screens cannot be guaranteed using the simple re-projection approach. The green dotted boxes demonstrate that the proposed method maintains the continuity, while the red dotted boxes show that the re-projection simply fails. Meanwhile, the computational cost of the proposed method is low because the warping of the image representation can be performed in real time once the optimal mesh is computed.

Fig. 17 depicts the seat arrangement of the example theatres and their associated suitability error E. The top row represents the appropriate theatres for ScreenX viewing while the bottom row represents the inappropriate theatres; the threshold E_{TH} for outlier culling was set to 0.2. As seen from the figure, the configurations of the inlier theatres are mostly similar, while those of the outlier theatres are inconsistent. The estimation of theatre suitability that focuses on similar experiences produces this tendency of classifying the theatres with somewhat similar structures as inliers.

Fig. 18 presents an example of the content created through applying the content production guidelines. The producers were directed to create content within the region overlaid with blue and green depending on the importance of the scene elements. As a result, the green region holds the important scene elements, such as the dashboard of the car and most of the outside scenery. The blue region holds an additional peripheral view of the outside scenery, which does not substantially influence the understanding of the scene, and it can be absent in some theatres. In this way, the guide image helps the producers predict the results before they are projected in the theatres.

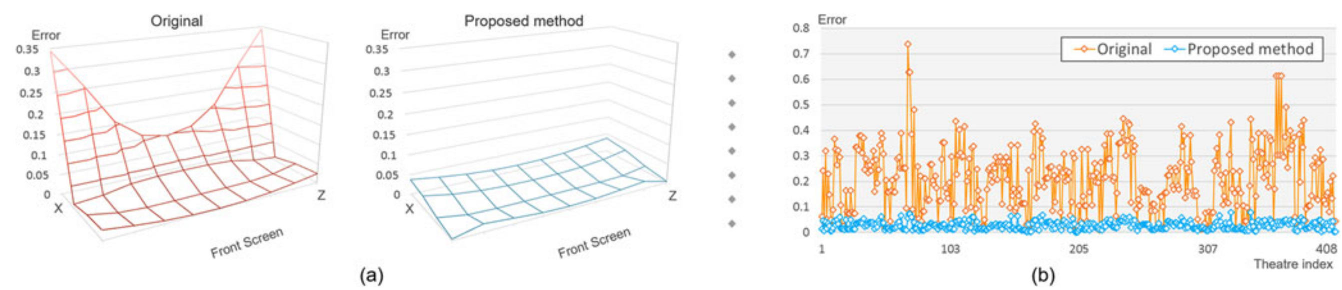

Fig. 15. Quantitative error comparisons of perspective distortions between the original content and the content resulting from the proposed method; (a) The error values of all seats in a theatre (The X- and Z-axes denote seat positions.) (b) The error values of all theatres in the database.

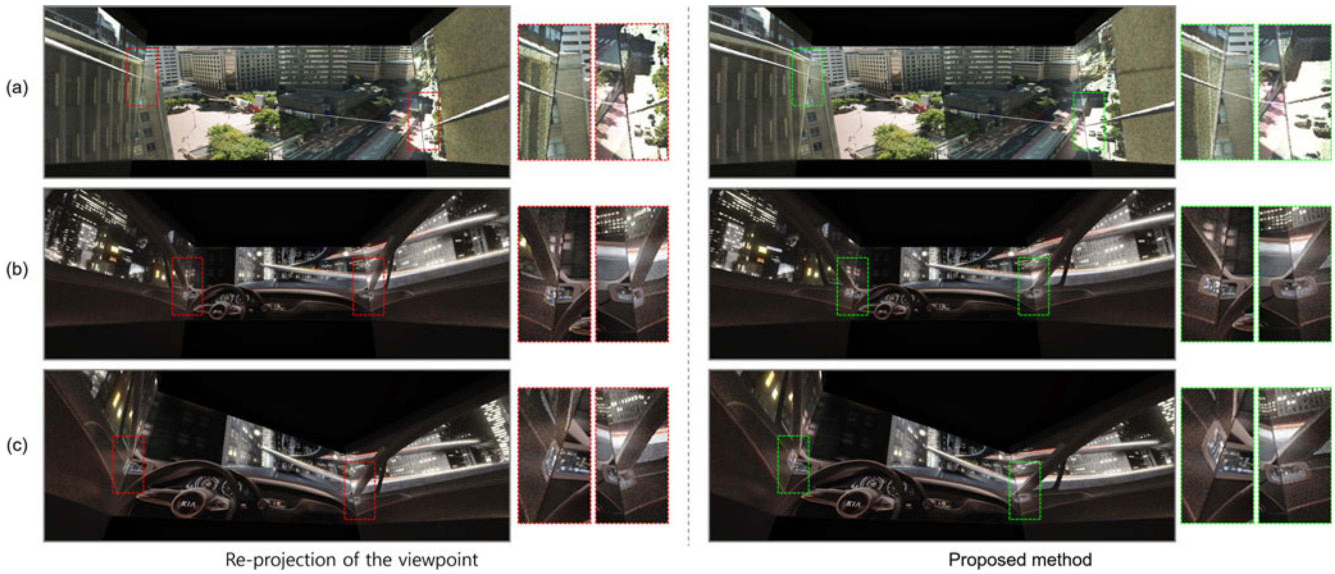

Fig. 16. Comparisons between the content produced via re-projection and via the proposed method. The dotted boxes indicate the enlargement of the important regions.

User study. Three different user studies were conducted with 17 participants (13 males, 4 females) in order to demonstrate the validity of the proposed image representation model. Note that the ages of the participants ranged from 25 to 34 years old and that gender differences were not considered important in any of these user studies. In the first experiment, the participants were presented with four sets of sample ScreenX images. The ScreenX image contained the original image and the result using the proposed method. The original image was projected consecutively while each participant changed their seat horizontally eight times. The same process was undertaken with the result of the proposed method. The viewing was repeated four times with random projection of the original image and the proposed method's result. After each viewing, the participants were asked the following question:

Q1: Which image provides more similar viewing experiences across the horizontal seat variations? A: *First image or second image*

In the second experiment, all participants were seated evenly in random positions throughout the theatre. They were presented with a three-minute long original ScreenX video scene displayed naïvely and a version produced using the proposed method consecutively and were asked the following question:

Q2: Which video provides a clearer image without distortion of the perspective? A: *First video or second video*

In the third experiment, the participants were presented with two sets of sample ScreenX images in a virtual theatre environment via Oculus [54] (see Fig. 19). Each set of images was displayed in six different virtually simulated theatres that have diverse dimensions and configurations. The first set corresponded to the original content, while the second set corresponded to the content created using the proposed method. The sets were projected in a random order. After each viewing, the participants were asked the following question:

Q3: Which set provides more uniform viewing experiences across the different theatres? A: *First set or second set*

For question 1, 68 (17×4) votes were received in total with 51 votes (75 percent) being in favor of the proposed method's result. The p-value in the exact binomial test was $4.453 \times 10^{-5} (< 0.05)$. This user study indicates that the results produced using the proposed method were considered to provide similar viewing experiences across horizontally different viewpoints significantly more often than those generated using the naïve method. In addition, the Pearson's chi-squared test was used to analyze the effects according to each test case. The estimated p-value was $0.02182 (< 0.05)$. This analysis also confirmed that the participants' selections were meaningfully in favor of the proposed method. For question 2, 13 (76.5 percent) out of 17 participants voted in favor of the proposed method's video and four participants (23.5 percent) voted in favor of the original video. The p-value of the proposed method's video in the exact binomial test was $0.04904 (< 0.05)$.

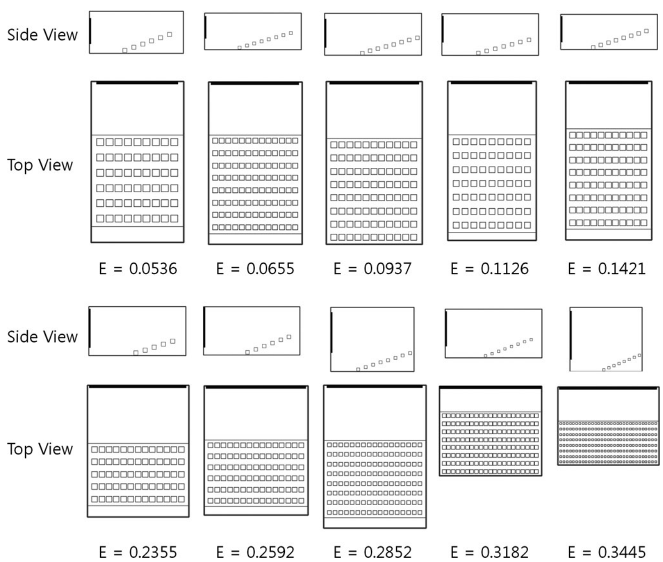

Fig. 17. The top row is the seat arrangement of the inliers with their theatre suitability error, and the bottom row is that of the outliers. The threshold value was 0.2.

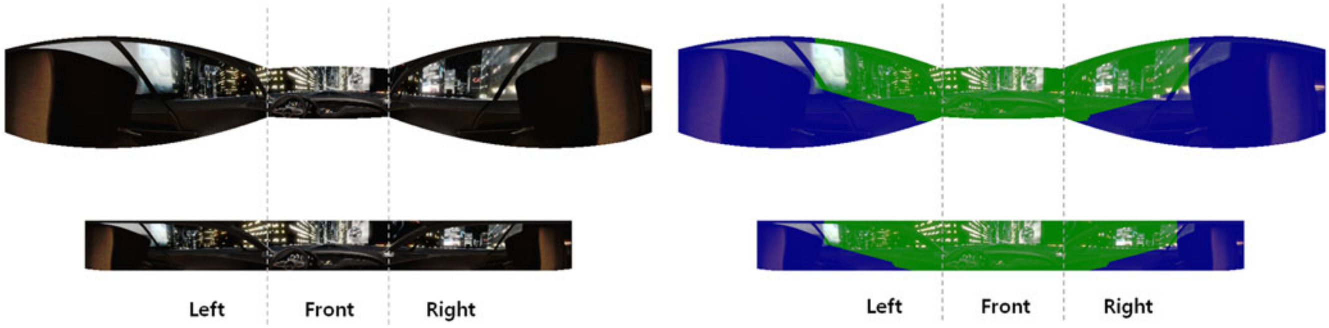

Fig. 18. The two left columns are examples of the content produced in the polar and image spaces. The two right columns are the images of the left column overlaid with the guide image. Please zoom in for details.

This user study indicates that the result produced using the proposed method was considered to provide a clearer image without distortion of the perspective significantly more often than that generated using the naïve method. However, the proposed method may adversely affect the visual experiences of the central viewing area for which there is little distortion, in order to increase the quality for the side seats which have larger distortions. Nevertheless, this user study confirmed that the proposed method provides better visual satisfaction through minimizing the average distortion of the entire seats. For question 3, 13 (76.5 percent) out of 17 participants voted in favor of the proposed method's result set and four participants (23.5 percent) voted in favor of the original set. The p-value of the original set in the exact binomial test was $0.04904 (< 0.05)$. This user study indicates that the result produced using the proposed method was considered to provide similar viewing experiences under diverse dimensions and configurations of theatres significantly more often than that generated using the naïve method.

Impact on industry. As ScreenX does not require significant modification to the current structures of the theatres, it is easy to covert an existing theatre to be ScreenX ready. Moreover, ScreenX has been successfully deployed in more than 80 movie theatres in Korea, Thailand, China, and America, and this number is growing rapidly. Accordingly, more than 50 commercial videos have been produced for ScreenX viewing (Fig. 20) and a large number of commercials have been proposed for production. In addition, the first movie natively shot for the ScreenX platform, which was a 30 minute short entitled *TheX*, was successfully showcased at Busan International Film Festival (BIFF) in 2013. Feature length blockbuster movies are currently under production in Korea [55]. The ScreenX system has recently been the stimulus for related industries to unveil similar multi-projection systems for immersive movie viewing under the name of Escape [56]. Considering this fast adoption by the industry, it is strongly believed that ScreenX has begun a new trend of immersive movie viewing worldwide.

Fig. 19. Images from a user study that evaluated the uniform viewing experiences across diverse movie theatres using virtually simulated theatre environments.

Fig. 20. Various examples of ScreenX content in action.

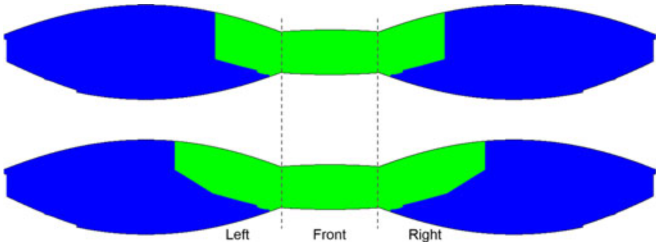

Fig. 21. The upper guide image was obtained through including all theatres in the database, 408 in this case. The lower guide image was produced after the removal of 22 outlier theatres with E_{TH} = 0.25.

8 Discussion and Limitations

8.1 Discussion

In order to model the weight w in Section 4, it was assumed that the viewers tended to concentrate on the front screen when they watched a ScreenX movie. This assumption is valid when the side screens are complementary to the front screen, e.g., display of simple patterns or effects, such as fireworks, snow falling, flames, glass cracking, and so on, which can help produce an immersive feeling while viewing the elements is not imperative. In contrast, if the content of the side screens includes important visual elements that assist in understanding the movie storyline, the viewers will actively follow the elements across the three screens. In this case, the formulation of the weight w should be modified accordingly. However, it remains unclear how to accommodate these situations because research related to an attention model for the ScreenX system has not yet been undertaken. This issue remains as future work.

The threshold value E_{TH} that determines the outlier theatres based on the suitability estimation can be adjusted according to different criteria. First, a movie theatre chain that is considering installing the ScreenX system may make their decisions based on economic considerations. Any threshold value based on budgetary constraints identifies the most appropriate theatres. These theatres can be selected first for the installation of the system within the current budget. Second, the threshold value can also be selected statistically. As seen in Fig. 9b, there is an interval that exhibits a rapid increase of E. A value in this interval can be selected as a natural default value. Third, the threshold value can be selected to maximize the size of the area that is visible in all theatres. Formulation of $\frac{\alpha}{\alpha+\gamma}$ indicates the rate of increase of the size of the area visible from all the theatres after culling each outlier theatre. Elimination of one problematic theatre can increase this value rapidly. Fig. 21 presents a comparison between the guide images before and after removing the outliers. Excluding the 22 outliers significantly expands the α region. In this manner, an appropriate set of theatres can be selected to show the created ScreenX content as optimally as possible.

In this paper, the issue of providing optimal and similar viewing experiences has been addressed. However, it would be interesting to investigate the degree of immersiveness according to the distance from the screen. A pilot study was conducted in order to determine seat preferences. All seats in the theatre were classified into one of three categories (*front*, *middle*, and *back*), depending on the distance from the front screen. Twenty-four participants were presented with a five-minute scene, which was repeated three times using the same content but with the participants sitting in different seat categories. The participants were asked to answer a question about their seat preference. The results demonstrated that none of the participants preferred the *front*. They commented that spatial immersiveness was lacking when seated in the *front* area. The *middle* was preferred by 11 participants, who commented that the sense of immersion was maximal in the *middle* due to the surrounded feeling. The *back* was preferred by 13 participants, who liked to look down on the entire three screens in a panoramic view. In the future, further research will be conducted in this direction.

As discussed in the introduction, ScreenX does not require installation of a physical silver screen on the side walls. Therefore, the quality of the projected image depends on the material used on the side wall. Furthermore, the resolution and brightness of the images projected onto the side walls are lower than those of the images projected by the main DCP, because inexpensive projectors are selected for projection on the side walls. In addition, wall fixtures such as speakers and exit doors may be present on the side walls. These factors can cause variations in the image quality on the main screen and on the side walls. A preliminary survey was conducted in order to determine if the difference in the image quality adversely affects the immersive viewing experience. Twenty-one participants were presented with a three-minute long ScreenX scene and were asked to answer the following questions:

Q1: Does the difference in visual quality between the front and side screens adversely affect the ScreenX movie viewing experience? A: *Yes or No*

Q2: Write down the reason for your answer to question 1.

For question 1, all participants answered *No*. According to their comments in question 2, several factors accounted for why they did not mind the difference in image quality. First, two participants commented that they did not notice the quality difference. Second, four participants commented that they perceived the quality difference, but it did not distract them as they were primarily focused on enjoying the content on the main screen. Third, 15 participants commented that they did not mind the quality difference because they enjoyed the new immersive movie viewing experience. As a result, it is clear that the current ScreenX system is a viable solution to provide immersive viewing experiences. Nevertheless, increasing the quality of the side content under suboptimal conditions remains a worthwhile future research topic.

The decision on how to present the ScreenX content is that of the movie producer or director. As a new means of storytelling, ScreenX can enrich their creativity in scene direction. They can direct the focus of the audience through only projecting the front screen, or they can utilize the three screens to maximize the level of immersiveness. Timely intermittent presentations of surrounding projections also assist with engaging the audience with the story effectively. Projecting the surrounding images throughout the entire duration of the movie is also possible if desired. However, formal experiments were not conducted on this issue in this study. Inadequate or excessive use of side projections may adversely affect the sense of immersion or may cause visual fatigue. Understanding these human factors is important and the scientific validation of how to present ScreenX content remains as future work.

8.2 Limitations

Image representation model. The proposed method is formulated in the 2D image domain. Although the distortions caused by differences in seat locations are minimized, the proposed method does not allow direct alteration of the 3D viewpoint of the content. Consequently, unnatural perspectives may result for seats located far from the reference viewpoint. However, the approach of view synthesis [53] may resolve this problem to some extent. In addition, straight lines such as the edges of buildings could become curved in the result because the context of the content is not considered in the optimization process. One potential solution could be the incorporation of context-aware content warping [44], [57]. It is acknowledged that these problems are important and they remain as topics for future research.

Theatre suitability estimation. The theatre suitability estimation effectively excludes outlier theatres. The remaining inlier theatres provide the audience with similar viewing experiences. However, strong evidence that these theatres are the best choices for experiencing the maximum sense of immersion does not exist. Therefore, it would be useful to conduct user studies to identify a "sweet spot" and theatres that have the ideal conditions for ScreenX viewing. This can be a challenging task because there are various factors to consider such as the position of the viewer, the structure of a given theatre, and the type of content. The pilot study will be improved and this issue will be investigated in more depth.

8.3 Open Issues

As a new movie viewing platform, ScreenX can stimulate and inspire further research and it will open up new research questions in various research fields. For completeness in this paper, three interesting open issues are identified and summarized here.

Multi-projection system. Building a multi-projection system in ordinary movie theatres is labor-intensive and time-consuming. Seats, wall fixtures such as speakers and exit doors, and the large scale of typical theatres make the application of camera-based automatic calibration methods difficult. In this study, the manual calibration of 10 projectors by one person required more than three hours. In addition, the coarse material of the side walls adversely affected the quality of the projected images. Furthermore, the side walls of some theatres have saturated colored material. Research in the field of rendering might lead to useful mathematical formulations that consider the wall material. Due to the different dimensions of theatres, each theatre requires the installation of a different number of projectors. An automated method for designing the multi-projection ScreenX system suited for diverse theatre environments would have practical importance.

Immersive content production. Compared with conventional movie content, ScreenX content has a very wide field of view (FOV) in order to cover the three sides of a movie theatre. The first ScreenX movie, *TheX* (2013), relied on a newly designed camera rig with three production cameras mounted together: a center camera for the front screen and side cameras for the side screens (see Fig. 22). Similar to the difficulties encountered in stereo camera calibration, inaccurate alignment between the three cameras can lead to artifacts around the boundaries between the front and side screens. Recently, Perazzi et al. [58] made significant progress in stitching videos from unstructured camera arrays. However, it can continue to be improved in situations with large displacements between cameras, lack of texture, and motion blur. Issues related to the camera calibration, synchronized postprocessing of the captured images, and compression/decompression of the data with increased size can be interesting problems to investigate. Furthermore, capturing content with panoramic setups is very difficult for the producer, because the very wide FOV restricts the lighting, stunts, and other normal cinematographic procedures.

Fig. 22. An example camera rig for the production of a ScreenX movie.

General research directions. In order to further enhance the viewing experiences, it would be interesting to combine ScreenX theatres with conventional stereoscopic viewing-enabled theatres. This combination itself is not new, but an attempt made specifically in the movie theatre environment can be meaningful. ScreenX enlarges the storytelling canvas from one screen to three screens. This enables new opportunities in movie directing. For example, a monster in a horror movie can appear from the back of the theatre through the side screens. Similarly, in a car chase scene a car can zoom past the audience along the side screens to the front.

9 Conclusion

In this paper, the ScreenX system was introduced; it is based on multi-projection techniques in order to provide immersive viewing experiences in ordinary movie theatres. ScreenX considers the left and right side walls as logical screens that work with the front screen. The proposed image representation model minimizes the average distortion experienced by the entire audience. The theatre suitability estimation effectively identifies outlier theatres, which results in similar viewing experiences across the selected theatres. The application of the guidelines during content production helps the producers determine in which areas the side scene elements can be placed. The validity of the proposed method was evaluated with various results and user studies.

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