DOI: 10.2352/ISSN.2470-1173.2016.21.3DIPM-404

Non-uniform resampling in perspective compensated large scale 3D visualization

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Abstract

The presented work addresses the problem of non-uniform resampling that arises when an image shown on a spatially immersive projection display, such as walls of a room, is intended to look undistorted for the viewer at different viewing angles. A possible application for the proposed concept is in commercial motion capture studios, where it can be used to provide real-time visualization of virtual scenes for the performing actor. We model the viewer as a virtual pinhole camera, which is being tracked by the motion capture system. The visualization surfaces, i.e. displays or projector screens, are assumed to be planar with known dimensions, and are utilized along with the tracked position and orientation of the viewer. As the viewer moves, the image to be shown is geometry corrected, so that the viewer receives the intended image regardless of the relative pose of the visualization surface. The location and orientation of the viewer result in constant recalculation of the projected sampling grid, which causes a non-uniform sampling pattern and drastic changes in sampling rate. Here we observe and compare the ways to overcome the consequent problems in regular-to-irregular resampling and aliasing, and propose a method to objectively evaluate the quality of the geometry compensation.

Introduction

During the past couple of decades the level of animation in movie and video games has greatly improved. The animation of humans, animals and other virtual creatures becomes more and more realistic. These all are possible due to the developments in motion capture technology [1], rapidly developing computer graphics technology, improvements in the power of computers and graphic cards. In motion capture a live motion of and object or a person is captured, digitized and mapped to a 3D virtual model that performs the same movements as the object being captured. Then the virtual model is placed into a virtual environment. When motion capture includes capturing face expressions and gentle movements, it is referred to as performance capture. The process of performance capture has a lot in common with the art of acting. Therefore, the actor's emotions, as well as subtle movements, play a significant role in the final result. In many cases, the actor is not merely overlaid into a virtual scene, but has to interact with purely virtual 3D content. Commercial motion capture systems are able to provide reasonable realtime visualization of the virtual scene to the director and cameraman (with the help of virtual camera systems), but crucially, not to the actor. The interviews of performance capture actors have shown that visualization solutions for motion capture studios provide an insufficient level of immersion with the virtual scene. The final result depends greatly on the ability of the actor to imagine the virtual scene, which becomes a serious problem when shooting is done for complex virtual scenes. Therefore, a proper visualization of virtual scenes for immersive actor feedback becomes an important issue. In the presented work we introduce an algorithm for a for view-dependent geometric correction in a CAVE-like environment. The rendered image of the virtual scene is pre-distorted based on the geometry of the visualization surfaces, so that the projected image looks undistorted to the viewer. A possible utilization of such a system is in commercial motion capture studios to provide an immersive feedback from the actor. As the actor moves within motion capture environment, the images shown on the walls are adapted to the viewer location such that the viewer receives the intended image regardless of the relative pose of the visualization surfaces. The introduced image based approach allows independence from the image source, creating a method that is more universally applicable. However, it also adds new kinds of problems, the most significant being the non-uniform resampling required to pre-distort the imagery. In the presented work we discuss the options of handling these sampling related issues and analyse their relative performance.

Prior work

The existing visualization technique in commercial motion capture studios is made with the help of a virtual camera system which is used for view-dependent rendering of the preconstructed virtual content. The rendered image is displayed either on the monitor mounted to the virtual camera rig or by the visualization display mounted to the wall of the motion capture studio. Since the display is in a fixed position, the actor easily loses track of the location and actions of unseen virtual characters, creating a mismatch between the real and virtual 3D worlds which prompts reshoots and manual work in post processing and decreases in the acting performance.

Other possible visualisation techniques include head-mounted displays (HMDs) [3, 4]. The obvious drawback of visualization techniques involving head-worn solutions is restriction of the actor with movements, which decreases the level of performance. Moreover, in most cases the actor also needs to see the real objects in the studio, such as props. Therefore, virtual reality solutions that substitute view to the real world, cannot be used in this case.

Different configurations of projectors available nowadays include small portable *hand-held* or *pico* projectors [5, 6], that can be held by the hands or attached to the head of the viewer for visualization of the virtual content. These solutions have similar drawbacks as other head-worn solutions described above.

The availability of different kinds of projectors enables creation of display surfaces that cover large visualization surfaces, such as seamless displays [8, 9, 10] and spatially immersive and semi-immersive displays [7, 11], that surround the viewer, pro-

DOI: 10.2352/ISSN.2470-1173.2016.21.3DIPM-404

viding a feeling of immersion with the displayed visual content. Spatially immersive displays enable creation of large scale visualization surfaces of different geometrical complexity, such as walls of a room, truncated domes or real objects. In order to compensate for visual distortions caused by the irregular geometry, color and texture of the visualisation surface, projected images are corrected in color and geometry.

A great deal of research was carried out in this area. Some of the methods are described in [12, 13, 14, 15]. The solutions use a projector-camera system to find the mapping between projector and camera pixels. Geometry correction of the imagery content is done by comparing the projected and the captured images.

Other projection-based systems provide view-dependent stereoscopic projection in real environments [12]. The most common approach for geometric warping in this case is using the pre-calculated 3D model of the visualization surface, which can be acquired by structured light, depth from stereo, depth from focus methods. For this a two-pass rendering technique, described in [7], is used there to render a perspectively correct imagery content. On the first pass, the view of the virtual scene from the perspective of the viewer is rendered. On the next step, the rendered image is texture mapped onto the visualization surface and rendered from the viewpoint of the projector [7]. A method for adaptation of the geometry and color of the imagery content also for dynamically changing environments is presented in [16].

The most common example of the use of spatially immersive displays is a CAVE (CAVE automatic virtual environment) [11], which is a rear projected virtual environment, having the shape of a room, with walls, floor and ceiling used as projection surfaces, in which a user feels fully immersed within a virtual environment. In this case the problem of geometry correction of the imagery content reduces to the problem of visualization on planar surfaces. The projector geometry and the geometry of projection surfaces is known a-priori. The viewer inside the room is head tracked so that the rendered image of the virtual scene retains the correct perspective. In order to render the content of the virtual scene, a perspective projection with asymmetric viewing frustum is used. A virtual camera is placed into a position of the viewer with the camera plane parallel to the projection surface.

The use of the CAVE-like system for motion capture studio is described in [2]. The system described there is a projection-based system which allows generation of the 3D models, as well as immersive actor feedback. The conventional rendering pipeline used in CAVE-like projection-based virtual reality systems is used there. The visualization surfaces are covered with retroreflective cloth, in order to compensate for unevenly distributed lighting conditions.

The problem of non-uniform sampling has been heavily studied in the past years. Different possibilities of sampling exist based on the nature of the data and sampling grid, such as regular-to-regular, regular-to-irregular, irregular, listed in the increasing difficulty. The methods that address the problems of reconstruction of band limited images from irregular samples are iterative reconstruction algorithms and adaptive weight methods [18, 19, 17]. The most common way for image reconstruction from irregular samples is by using splines [20]. The way to approach the problem of geometry correction in the presented paper is the reconstruction of the image from the regular samples, which can be done with conventional interpolation methods such as nearest-neighbour, linear, cubic and spline interpolation. Therefore, we do not describe the irregular-to-regular methods in more detail.

Description of the use case

The proposed solution is a projection based CAVE-like system that is able to make the motion capture environment more immersive by providing the actor with proper real-time visualization of virtual content. The system combines the aspects of projection-based spatially immersive displays, and optical tracking to give actors a sense of immersion with the virtual scene. A proposed CAVE-like system is depicted on Figure 1. An actor

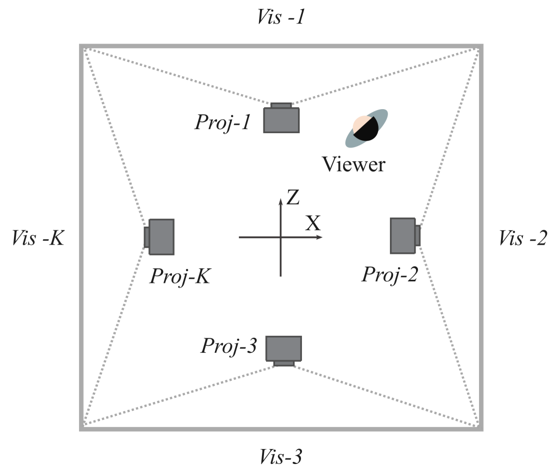

Figure 1. *System overview. A tracked viewer is inside the motion capture volume. Each projector (Proj-1, ..., Proj-K) is related to a visualization surface (Vis-1, ..., Vis-K).*

inside the motion capture studio is tracked by the optical trackers. The main components of the system are: a tracked actor, projectors *Proj-1*, ..., *Proj-K*, and their corresponding visualization surfaces *Vis-1*, ..., *Vis-K*, with K - the number of projectors. The components of the system are placed in the world coordinate system, defined by the tracking system. The system assumes use of a 3D rendering engine (e.g. virtual camera system used in the virtual camera rig) to render an image $f(x,y)$, $x = 1,\ldots,M$, $y = 1,\ldots,N$, of the virtual scene from the viewpoint of the actor. The location and orientation of the actor's head position is extracted from the data received from the motion capture system. As the actor moves through the volume, the images from the virtual rendering engine, shown on the walls, are geometry corrected based the the viewer location such that the viewer receives the intended image regardless of the relative pose of the visualization surfaces.

View-dependent geometry correction

Regardless of the imagery content to be shown at the visualization surface, the components that define the geometry warping are the *visualization surface model*, the *projector model* and the *location and orientation of the viewer*. The walls of the motion capture room are considered as visualization surfaces, ideally covering the full field of view of the actor. The configuration can be simplified by not filling the full filed of view of the actor, which will lead to the gaps in the visualized content, depending on the

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DOI: 10.2352/ISSN.2470-1173.2016.21.3DIPM-404

location and orientation of the viewer. Projection surfaces are assumed to be planar with known dimensions. Each projector has an optical axis orthogonal to the display surface and illuminates a planar rectangular area.

Let the number of projectors be K, with each projector related to a visualization surface. The display surface model is constructed by associating each projector pixel $\mathbf{x}_p = [x_p, y_p]^\mathrm{T}$ with a 3D pixel position $\mathbf{X}_p = [X_p, Y_p, Z_p]^\mathrm{T}$ lying on the visualisation surface, which is modelled as a plane. A 3D model of the visualization surface is obtained from at least 3 points that lie on that surface. The coordinates of these points are given by the markers placed in the corners of the rectangle illuminated by a projector. The visualization surfaces Π_i are characterized by 3×4 matrices of corner coordinates A_i, their normal vectors $\mathbf{n}_i = [a_i, b_i, c_i]^\mathrm{T}$, and distances from the origin of the system to the plane d_i, $i = 1, \dots K$. For each point $\mathbf{X}_{p_i} = [X_{p_i}, Y_{p_i}, Z_{p_i}]^\mathrm{T}$ lying on the surface $\{\mathbf{n}_i, d_i\}$ the following holds

$$\mathbf{n}_i \cdot \mathbf{X}_{p_i} + d_i = 0,\ i = 1, \dots K, \tag{1}$$

where $\cdot$ is a dot product. The 3D model of the pixel grid is found by defining the 3D model in the origin of the global coordinate space, and then translating it to the position of the visualization surface. A 3D vector of coordinates of each 3D point $\mathbf{X}_{p_i} = [X_{p_i}, Y_{p_i}, Z_{p_i}]^\mathrm{T}$ illuminated by a ray through the ith projector center and 2D projector pixel $\mathbf{x}_p = [x_p, y_p]^\mathrm{T}$ is found as

$$\begin{bmatrix} X_{p_i} \\ Y_{p_i} \\ Z_{p_i} \end{bmatrix} = R_{p_i} \begin{bmatrix} s_{x_i}(x_{p_i} - c_{x_i}) \\ s_{y_i}(y_{p_i} - c_{y_i}) \\ 0 \end{bmatrix} + \begin{bmatrix} C_{X_i} \\ C_{Y_i} \\ C_{Z_i} \end{bmatrix},\ i = 1, \dots, K, \tag{2}$$

where R_{p_i} is a 3×3 rotation of the visualization surface with respect to the tracker coordinate space s_{x_i}, s_{y_i} are the sizes of illuminated pixels, $[c_{x_i}, c_{y_i}]^\mathrm{T} = [M_{p_i}/2, N_{p_i}/2]^\mathrm{T}$ is the principal point on the image plane of the projector and $[C_{X_i}, C_{Y_i}, C_{Z_i}]^\mathrm{T}$ is the principal point of the illuminated rectangle in the global space and $M_p \times N_p$ is projector resolution. Scale factors are found by $s_{x_i} = M^{\mathrm{m}}_{p_i}/M_{p_i}$, where $M^{\mathrm{m}}_{p_i}$ is the length of the side of the illuminated rectangle in meters. The process of geometry correction of the image $f(x,y)$ from the rendering engine is shown in Figures 2, 3. We put a

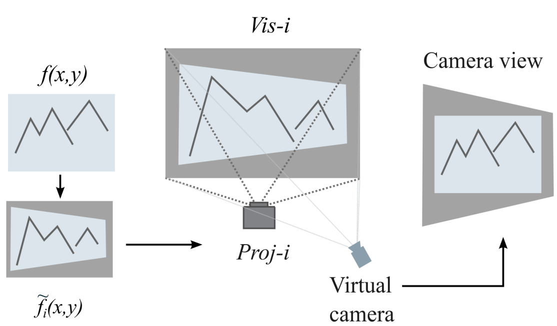

Figure 2. *Geometry correction of the image.*

virtual pinhole camera to the location of the viewer, and the image from the virtual engine, $f(x,y)$, with the dimensions $M_c \times N_c$, to the virtual camera plane. Therefore, the extrinsic parameters of the virtual camera are characterised by the translation vector $\mathbf{t}$ and rotation matrix R_c of the viewer.

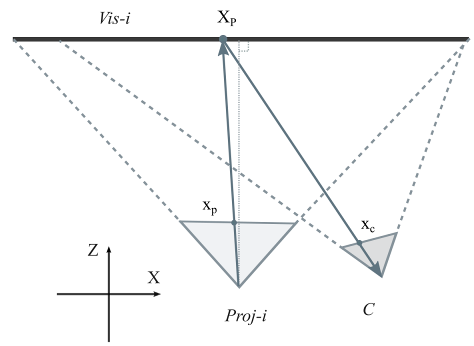

Figure 3. *Top-down view on the system.*

A geometry corrected image $\tilde{f}_i(x,y)$, for each visualization surface i, $i = 1, \dots, K$, i.e. the intensity value of each point on the visualization surface illuminated by the corresponding projector light ray, is formed by central projection mapping of that illuminated point to the virtual camera plane and consecutive interpolation of the color value. Each 3D point $\mathbf{X}_{p_i} = [X_{p_i}, Y_{p_i}, Z_{p_i}]^\mathrm{T}$ that represents ith projector pixel is mapped to the 2D camera plane as a point $\mathbf{x}_c = [x_c, y_c]^\mathrm{T}$ (in homogeneous coordinates) by a central projection mapping

$$\tilde{\mathbf{x}}_c = K_c [R_c | \mathbf{t}] \tilde{\mathbf{X}}_p, \tag{3}$$

where $\mathbf{t} = -R_c \tilde{\mathbf{C}}$, K_c is the the matrix of intrinsic parameters, and C is the position of the viewer's head. The diagram of geometry correction steps described above is shown in Figure 4.

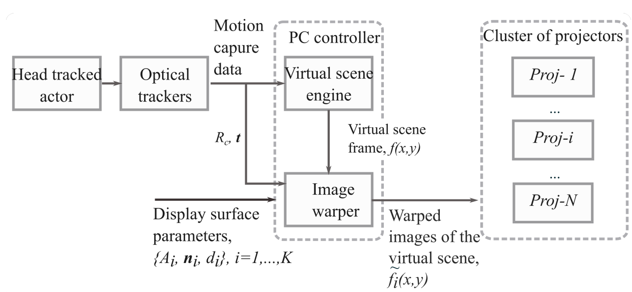

Figure 4. *Input and output parameters of the system.*

Non-uniform sampling and anti-aliasing

The changes in location and orientation of the viewer result in constant recalculation of the projected sampling grid, which causes a non-uniform sampling pattern and substantial changes in sampling rate. In the described case the problem assumes regular-to-irregular sampling of the projected points over the uniform grid of the image in the virtual camera plane. Depending on the relative position and orientation of the viewer and visualization surface, the resulting irregular grid of projected points has different configurations (e.g. shown in Figure 5), which are caused by perspective distortions. In order to prevent aliasing, low-pass filtering is done. The cut-off frequency for the low-pass filter is calculated from the worst case sampling step k in the non-uniform pattern, which is calculated based on the maximum Euclidean distance

DOI: 10.2352/ISSN.2470-1173.2016.21.3DIPM-404

between the closest projected grid points,

$$k = \max\{\mathrm{d}(\mathbf{x}_m, \mathbf{x}_n) \mid \mathbf{x}_m, \mathbf{x}_n \in \mathbb{R}^2\}, \tag{4}$$

where $m = 1, \dots, M_{p_i}$, $n = 1, \dots, N_{p_i}$, $i = 1, \dots, K$ and the Euclidean distance between points $\mathbf{x}_m$, $\mathbf{x}_n$ is calculated via

$$\mathrm{d}(\mathbf{x}_m, \mathbf{x}_n) = \sqrt{(x_m - x_n)^2 + (y_m - y_n)^2}. \tag{5}$$

The low-pass filter cut-off frequency f_{cut} is calculated from k as $f_{cut} = 1/(2k)$. The conventional Gaussian, Butterworth, Kaiser window filters are used further to low-pass the image.

Image reconstruction as a least-squares problem

In the presented work we use a least-squares tensor-product spline [20] for regular-to-irregular sampling. The tensor product of two functions $h(x)$ and $g(y)$ is a bivariate function $f(x,y) = h(x)g(y)$. Therefore, regularly spaced 2D data can be expressed via tensor product splines. Let the coefficient α_i be from a spline space $\mathbb{S}_{h,\mathbf{l}}$ formed by a span of m splines of order h of a non-decreasing knot sequence $\mathbf{l} = [l_1, \dots, l_{m+h}]^{\mathrm{T}}$, i.e. $\alpha_i(y) = \sum_j^m \alpha_{ij}\beta_{j,h}(y)$, which gives a tensor product of two spline spaces

$$f(x,y) = \sum_{i=1}^{m}\sum_{j=1}^{n} \alpha_{ij}\beta_{i,k}(x)\beta_{j,h}(y), \tag{6}$$

in the linear spline space $\mathbb{S}_{k,\mathbf{t}} * \mathbb{S}_{h,\mathbf{l}}$, with $*$ denoting tensor product in spline space. The least squares method is commonly used to fit a surface or a curve to a given data. A least-squares spline is formed from the image data points, corresponding to the new sampling rate. This allows the smoothing that is needed to prevent aliasing in the reconstructed result, which results from changes in the sampling rate of the re-sampled points. Then, the spline is used to re-sample the irregular samples at the new regular grid. For a gridded data with known data points $f(x_i, y_j)$, $i = 1, \cdots, N$, $j = 1, \cdots, M$ the weighted least squares problem is to find an approximation $\hat{f}(x_i, y_j)$ that minimizes the residuals

$$\min_{\hat{f}(x,y) \in \mathbb{S}_{k,\mathbf{t}} * \mathbb{S}_{h,\mathbf{l}}} \sum_{i=1}^{M}\sum_{j=1}^{N} w_i v_j \left[\hat{f}(x_i, y_j) - f(x_i, y_j)\right]^2, \tag{7}$$

where x_i, y_j are the non-decreasing sequences of known data sites at some intervals $[a,b]$, $[c,d]$, and $w_i \geq 0$, $v_j \geq 0$ are the weights and the spline approximation surface $\hat{f}(x,y)$ is given by a tensor product [20].

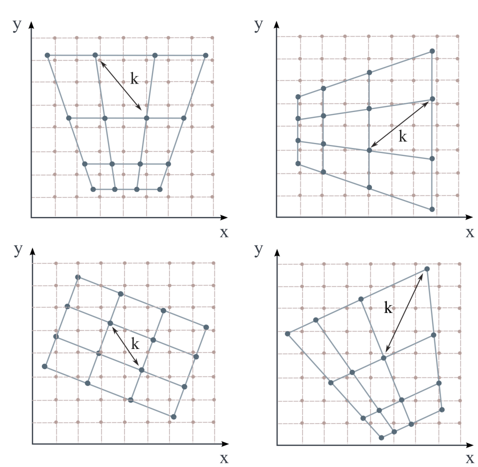

Figure 5. Examples of resampling grid (dark-grey line) of mapped projector pixel centroids, resulted from rotations along X and Y axes (top), Z and X,Y,Z axes (bottom) and the sampling step k.

Mesh-based performance evaluation

We would preferably evaluate the quality using objective metric, such as PSNR. However, due to effects like camera response function, lens distortion, and tracking error, perfect alignment required by such metrics is difficult to achieve in practice. Instead, we propose a mesh based simulation model for performance evaluation of the described method. Formation of the image content by a projector, whose optical axis is orthogonal to the visualization surface is approximated by piece-wise constant functions, i.e. rectangular projector pixels. These piece-wise constant functions form a polygonal mesh with each polygon corresponding to a pixel in the surface. Each pixel is modelled by 3D vertices placed in the corner places of pixel rectangle. The mesh is represented by the described set of vertices and the set of faces (polygons), with each face having the color of the corresponding pixel. The same central perspective projection described above is used to project the mesh in the display domain to the virtual camera, located at the desired viewer position. Then, the mesh is rasterized at high resolution. Forming a mesh out of the reference image $f(x,y)$ in the virtual camera plane and rasterizing it in high resolution can cause spatial domain artefacts in the reference image. Therefore, the reference image $f(x,y)$ in the virtual camera plane is upsampled by an integer factor with a nearest neighbour interpolation, and the rasterization factor of the projected mesh is chosen to provide the same resolution as the upsampled reference image. In this way, the effect of the perspective distortion is modelled, but images can be perfectly aligned and e.g. PSNR can be computed. The block diagram of the evaluation method is given in Figure 6. Figure 6 shows how geometry corrected images $\tilde{f}_i(x,y)$, $i = 1, \dots K$, formed for each display surface based on the position and orientation of the viewer inside the room, contribute to the final image formed at the virtual camera plane. Each mesh of geometry corrected image $f_i(x,y)$ is projected to the camera plane and contributes the final mesh by forming a part of the reference image $f(x,y)$.

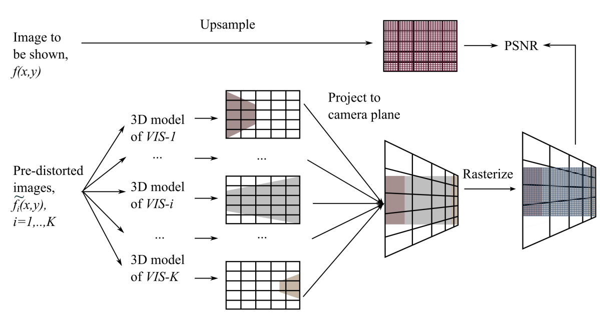

Figure 6. Proposed image quality evaluation scheme.

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DOI: 10.2352/ISSN.2470-1173.2016.21.3DIPM-404

Experimental results

The overall functionality of the implemented system is verified through a simplified setup shown in Figure 7: a front-projected visualization surface, an optical tracker and a camera put into the place of the tracked viewer. Images taken by the tracked camera are analyzed for their geometrical distortions. From the images captured from the test setup, two metrics, rectangularity and the deviation of the corner angles were measured. The rectangularity was measured by a minimum bounding rectangle method [21], where the rectangularity is the ratio between the area of the region and the area of the its minimum bounding rectangle (MBR). The results are shown in Figure 8, 9. For reference, the same measures are presented for the same image but without viewer position compensation. The captured image has a high rectangularity measure of around 0.95 and low angular deviation of 1-2 degrees even the extreme angles, which shows that the system is able to compensate for the different viewing angles.

A comparison between several conventional regular-to-irregular sampling schemes for rendering the warped image is presented in Figure 10 using the proposed mesh based quality evaluation. Intuitively the most influential parameter being the angle between the viewing direction and the display surface, the PSRN results are shown for this case. Nearest neighbor, linear, cubic, spline and least-squares spline interpolation are compared together with an application of an adaptive anti-aliasing filter. The results show that the least-squares spline provides better results.

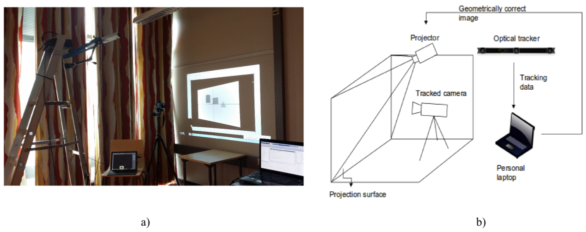

Figure 7. *A photo (a) and a diagram (b) of the experimental setup.*

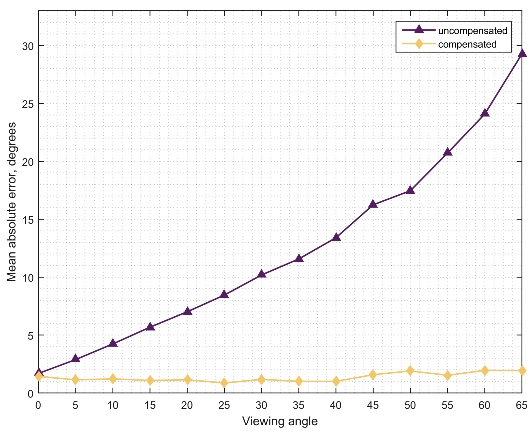

Figure 8. *Deviation from 90 degrees of the pre-distorted image (yellow) and uncompensated (magenta) captured from the position of the virtual camera with different viewing angles.*

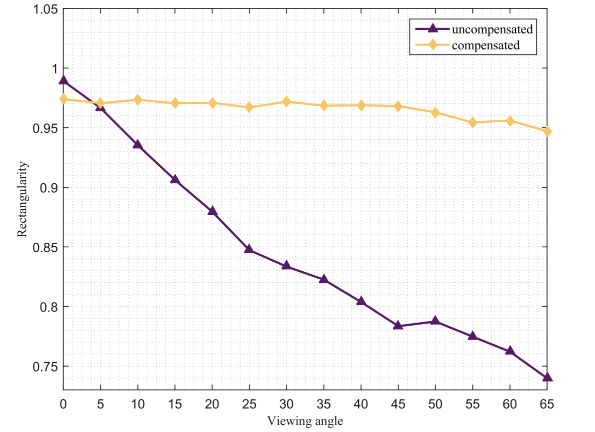

Figure 9. *Rectangularity of the pre-distorted image (yellow) and uncompensated (magenta) captured from the position of the virtual camera with different viewing angles.*

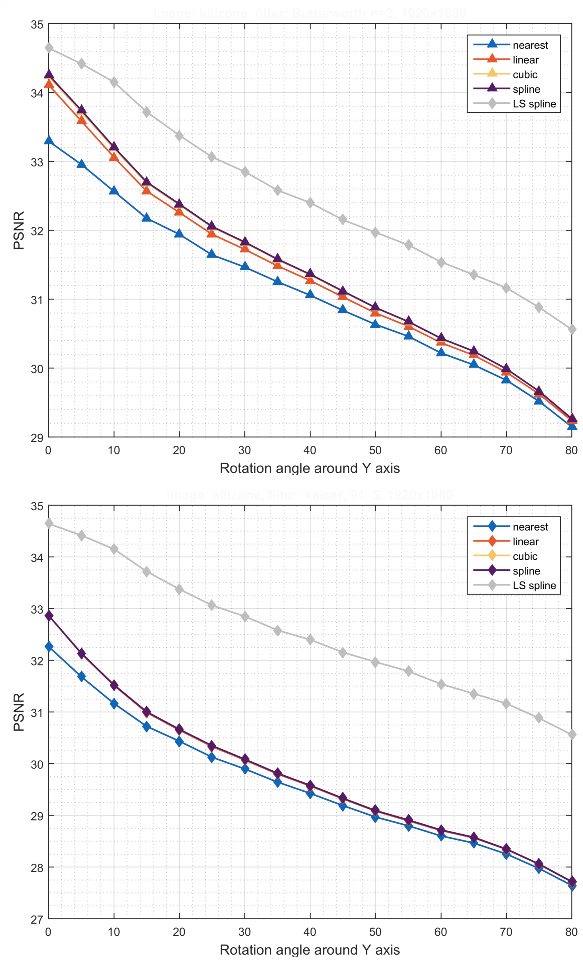

Figure 10. *Comparison of the quality produced by different interpolation techniques with anti-aliasing done with Butterworth (top), Kaiser (bottom) filters for the image of resolution* 1920×1080 *and projector resolutions* 1920×1080 *and least-squares splines (grey line).*

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With the simulation framework in place, more comprehensive data and more detailed analysis of the effect of different parameters was conducted: rotation angle, image and display resolution, anti-aliasing filtering. The following regular-to-irregular sampling schemes for rendering the warped image were tested:

- Low-pass pre-filtering with Kaiser window and nearest/(bi)linear/ (bi)cubic and cubic spline interpolation.
- Low-pass pre-filtering with Butterworth filter and nearest/(bi)linear/ (bi)cubic and cubic spline interpolation.
- Low-pass pre-filtering with Gaussian filter and nearest/(bi)linear/ (bi)cubic and cubic spline interpolation.
- Resampling as a least squares fit.

Also, an effect of image and display resolutions was tested. The PSNR for the following cases was compared:

- Image resolution $>$ projector resolution.
- Image resolution $<$ projector resolution.
- Image resolution $=$ projector resolution.

A useful finding is that for the case when image resolution $<$ projector resolution. For this case, the best interpolation scheme for all anti-aliasing filters is nearest neighbour. The results for this case are shown in Figure 11. The reason of the result shown at Figure 11 is that the projector resolution is much higher, which is sufficient to provide the best approximation of the source image. For the cases when image resolution $=$ projector resolution, the best interpolation technique is provided by splines (Figure 10). For the cases when image resolution $>$ projector resolution, all the interpolation schemes show fair results.

Conclusion

Currently it is possible to provide good visualization to other crew members in a motion capture environment except the actor. The contribution of the presented work is to develop a tool for providing also the actor with proper visualization of the virtual content without confining him/her with additional peripherals like VR glasses. The approach taken has similarities with CAVE-like virtual reality systems, but the use context is new. Furthermore, the system applies an image based rendering approach to make it independent of the input image source, which makes it applicable for using with any existing rendering engine and compatible even with modern approaches such as light field based content.

The proposed mesh based quality evaluation solves an important alignment issue with computing objective quality metrics, and may find other uses in other applications where e.g. the quality of spatially immersive displays is evaluated. The relatively simple model can also be extended with additional effects such as nonuniform intensity of pixels or non-Lambertian display surfaces to achieve a more accurate simulation.

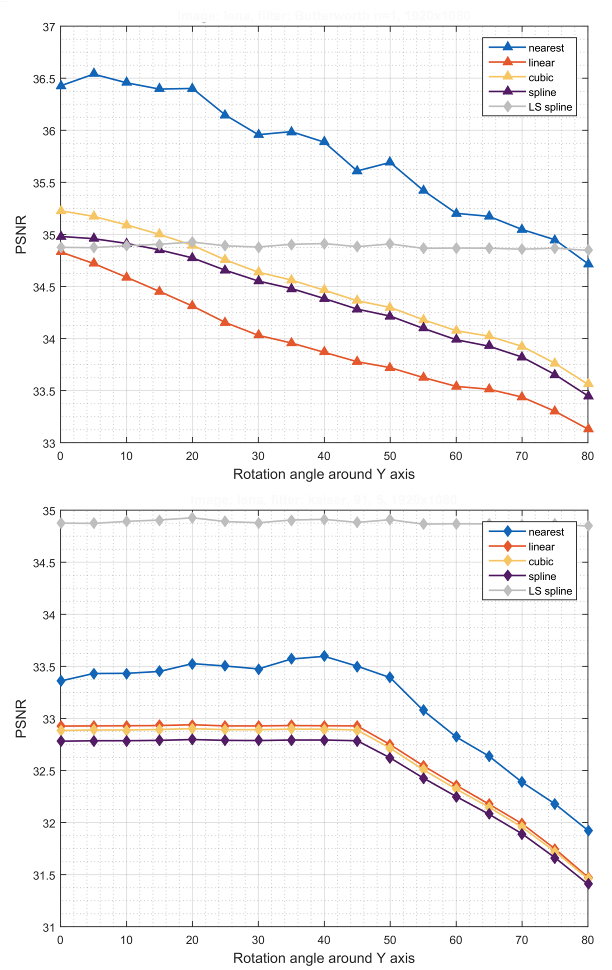

Figure 11. *Comparison of the quality produced by different re-sampling techniques for the (lena) image of resolution* 510×290 *and projector resolutions* 1920×1080 *with Kaiser filter.*

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