Virtual Navigation of Complex Scenes using Clusters of Cylindrical Panoramic Images

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Abstract

The traditional approach of generating novel virtual views of an object or a scene is to render the appropriate 3-D model. The alternative is to render directly from the original images; this approach, which is based on pixel interpolation or reprojection, is called *image-based rendering*. In this paper, we describe a technique that enables virtual navigation within a complex environment using an image-based rendering technique. In particular, we make use of *clusters* of cylindrical panoramic images. Each cluster of panoramic images allows the user to smoothly navigate within a particular area, say within a single room. Having a collection of such interconnected clusters would enable the user to seamlessly navigate within a complex environment, such as an entire floor of a building, with each cluster representing a room. To achieve this goal, we examine a few techniques for image-based rendering using a cluster of cylindrical panoramic images to synthesize views from virtual viewpoints. We also describe our method for enabling smooth transition between clusters.

Keywords: Image-based rendering, virtual reality, cylindrical panoramic images.

Introduction

The ability to synthesize new views from many different virtual viewpoints is important in many current and future applications, in areas that range from games and entertainment to business (e.g., real estate, tourism) and education. A typical application would involve real-time interactive walkthroughs within a virtual environment. The scene to be displayed remains the same, but the view position and direction of the virtual camera are controlled by the user.

The traditional method for producing such walkthroughs is based on 3-D model-based rendering, where views are generated by directly rendering 3-D models at specified viewpoints. The 3-D representation of the object or scene can either be created using a geometric modeler or from real data. Real 3-D data can be obtained using a 3-D digitizer or a rangefinder, or by applying a stereo algorithm on multiple images of the same scene or objects at different camera viewpoints. In scientific or biomedical visualization, the input data may be multidimensional.

In the specific case of visualizing 3-D objects or scenes, the resulting virtual views can be made more photorealistic by either texture-mapping images of actual objects onto the surfaces of models, or simulating surface properties using physically-based reflectance models. However, it is difficult to produce photorealistic images in a timely fashion without the use of both sophisticated and expensive rendering software and graphics hardware accelerators.

An alternative method for rendering is to create new views directly from images, called image-based rendering. Novel virtual views created using this approach can be as high a quality as the input images. As a result, it can be relatively easy to produce photorealistic images from images of real scenes. The philosophy of image-based rendering is that all the information for rendering is available in the images themselves.

We are particularly interested in developing an image-based rendering system that allows a user to smoothly navigate within a large and complex environment (such as a multiple room environment). While there are techniques to allow navigation within a restricted range of virtual camera motion [1, 7], none has addressed the problem of allowing virtual navigation along a long, continuous path.

Previous work

There is a significant amount of work done involving visualization of wide scenes, some of which have been commercialized with some degree of recognition and success. A notable example of such a commercial product is Apple's QuickTime VR^{TM} [1]. With this product, the

user is able to pan and tilt the virtual camera to view (after dewarping) a section of a cylindrical panoramic image of a real scene. Other commercial products are based on a similar principle, such as Infinite Pictures' SmoothMove, IBM's PanoramIX, and RealSpace, Inc.'s RealVR$^{\mathrm{TM}}$. Instead of using cylindrical panoramic images, Interactive Pictures Corp.'s IPIX (formerly Omniview's Photobubble) uses spherical images instead.

On the research front, mosaics are constructed to represent a wide scene; examples include rectilinear panoramic images (e.g., [10]), cylindrical panoramic images (e.g., [1, 7, 4]), spherical mosaics [14, 12], super-resolution images (e.g., [3]), image mosaics with identified multiple motions (e.g., [9, 13]), and image mosaics with identified parallax (e.g., [5]). However, only cylindrical and spherical mosaics allow 360° viewing in at least one direction. Out of the work listed, only [7] and [4] allow virtual navigation involving arbitrary translational motion. This is done using multiple cylindrical mosaics. Both systems are restricted to viewing of one wide scene. One approach to viewing a complex, interconnected set of wide scenes is to construct the appropriate 3-D model and render it. For real scenes, constructing such a 3-D model is difficult to achieve with high accuracy without resorting to using accurate, expensive rangefinders.

The goal of our work is to enable smooth virtual navigation along a long, continuous path within a large complex environment. An example of such complex environment is a multi-room floor of a building, where one or a small number of panoramic images taken at close proximity to each other is not sufficient to visualize and represent the entire environment. There are two options to realize this goal:

- Use a relatively dense sampling of panoramic snapshots of the entire environment, or
- Use a select number of clusters of panoramic snapshots strategically chosen to represent the environment.

For a very large environment, option (1) would require a very large number of panoramic images, which will be very expensive in terms of both memory and computational requirements. In addition, there are other difficult issues that have to be addressed. One such issue is choosing the appropriate subset of panoramic images to create the virtual view. Furthermore, automatically extracting a consistent scale of relative camera distances between projection centers of panoramic images across the entire set of panoramic images is difficult due to drifting and error propagation. We use option (2) instead, which is a good compromise between requiring high memory and computation and reasonable visualization. Here, the "appropriate" sets of panoramic images are predetermined; in addition, scale consistency is less of an issue between panoramic clusters. The tradeoff would result in the user not being able to navigate and get high quality image reconstruction at all viewpoints. The idea for option (2) is shown in Figure 1.

This paper also explores some of the techniques for image-based rendering. For modeling wide scenes that have a angular span close to or greater than 180°, flat images are mathematically unwieldy. Cylindrical and spherical panoramic images offer a much better mathematical generalization for modeling such a scene. The approach that we use is to reproject the pixels in a geometrically consistent manner. As in [7], we use cylindrical panoramic images as input, though the concept can be extended to spherical images as well.

General idea–Using multiple panoramic clusters

In work such as those of [7] and [4], the user has the ability to view the scene at any vantage point, even at locations not coincident with any of the projection centers corresponding to the previously recorded images. However, they are restricted to visualization of a single wide scene at a time. We add to this the ability to not only move within a wide scene, but to move from one wide scene to a different wide scene in a smooth, seamless manner. We represent each wide scene with a cluster of panoramic images, each cluster consisting of at least three panoramic images. This idea is depicted in Figure 1. Travel between clusters is through an access point called a "hotspot," using the term for Apple's QuickTime VR$^{\mathrm{TM}}$.

In comparison with unconstrained navigation within a cluster, traveling between clusters is necessarily restricted due to the limited visual overlap. In our implementation, between-cluster travel is constrained to an approximation of one degree-of-freedom translational motion. This motion is only approximate because we use interpolated affine global motion. This is reasonable as long as the 3-D location of the "hotspot" is far away in comparison with the between-cluster baselines, which, in our case, is true. On reaching the destination panoramic cluster, information from previous cluster representing the previous wide scene is discarded and the information representing the destination wide scene is automatically loaded. This information is now used for virtual navigation in the second wide scene until the user opts to move to another wide scene by clicking at another "hotspot." (Note that the wide scene information have been computed off-line.)

Extracting information for a panoramic cluster
We assume that the distance between camera centers (or baseline) within a cluster of panoramic images are small enough so that there is almost complete visual overlap between the constituent panoramic images. This allows automatic (or in the worst case, guided) registration to be performed.

As mentioned earlier, the scene to be modeled is assumed to be a static scene. For ease of modeling wide scenes, we require cylindrical panoramic images. The input is obtained by taking a sequence of images while rotating the camera about a vertical axis passing through the camera projection center. The panoramic image is a composite of these rotated camera images [7, 4]. At least two cylindrical panoramic images are needed to capture the geometry of the scene.

Pixel correspondence between pairs of panoramic images is obtained by using the spline-based registration technique, which attempts to deform a mesh in order minimize the intensity difference between the first image (used as reference) and the warped second image [11]. Once we have the pixel correspondences, we use the 8-point algorithm [6] to recover the camera parameters and position up to a scale factor. An example of a cluster of panoramic images and its recovered structure is shown in Figure 8. As before, the left part of Figure 8(a)-(e) and (j) are the top view of the rough shape of the current environment. Note that the dot and arrow (in red) indicate the location and direction of view that corresponds to the right image part.

Rendering techniques within a cluster
In this section, we describe the techniques that we have implemented for the image-based rendering using cylindrical panoramic images within a cluster. The rendering is basically done in two phases: (1) The forward mapping phase, during which pixels from the given cylindrical panoramic images are mapped onto the virtual cylinder, and (2) The inverse mapping phase, during which holes or missing pixels in the virtual cylinder are filled. This two-phase approach is adopted primarily for speed considerations.

Forward mapping
Forward mapping refers to the process of projecting pixels in texture space (available panoramic images) to the final screen space (rendered virtual view). This simple idea is depicted in Figure 2. The forward mapping process is equivalent to finding the 3-D point associated with the two corresponding points in real panoramic images 1 and 2, and then projecting the point onto the virtual panoramic image (corresponding to a virtual camera position). The final rendered virtual view is the dewarped or "flattened" version of the frontal section of the virtual panoramic image. Note that the accuracy of image transfer is dependent on the accuracy of point correspondence across the real panoramic images.

One fundamental issue that has to be handled in rendering new images correctly is that of object occlusion, or depth ordering.

Occlusion
The forward mapping is a many-to-one mapping, and this is caused by object occlusion. As a result, occlusion has to be handled correctly in order to generate correct views from virtual viewpoints. A straightforward but inefficient method for handling occlusion information is to compute depth at every pixel and apply the usual z-buffering technique. However, as noted by McMillan and Bishop [7], a depth buffer is not necessary if we can find a simple back-to-front ordering as shown by the directions of traversal in Figure 3. This ordering is indexed simply by the cylindrical angular coordinate in the cylindrical reference view.

Speeding up forward mapping
We approximate the limited human visual field with a 160×160 square viewing window. This viewing window is usually much smaller than the size of the cylindrical panoramic image. We can take advantage of this fact to speed up the reprojection computation. In other words, the main speedup in rendering virtual views comes from the fact that we are not computing the entire virtual cylinder, but rather only a small portion of the virtual cylinder.

The selective scanning over the reference cylinder is divided into four cases based in the relative position of the reference cylinder with respect to the pyramid of view. The apex of the pyramid is coincident with the optical center of the virtual cylindrical panoramic image. The four cases are illustrated in Figure 4, with the pyramid of view shaded, the reference panoramic image shown as solid circles, and the virtual panoramic image shown as a dashed circle. For each of the cases, the regions appropriate for scanning are in solid thick arcs.

Case 1: The center of the reference camera lies in the view pyramid. At first glance, it would seem that in this case, no speed up is possible as the pixels on the virtual cylinder could get their values from any of the pixels on the reference cylinder. As a result, it would appear that a complete scan is necessary to ensure the correctness of the algorithm.

However, we can assume that there are no objects closer to the projection center of the reference panoramic image than a user-defined distance $r_{\min}$. A reasonable value of $r_{\min}$ is 10 (relative to the

unit baseline length between projection centers of the reference panoramic image and a second given panoramic image). With this assumption, the range of scan can then be restricted considerably (see Figure 4).

Case 2: The center of the virtual camera lies in the view pyramid of the reference camera. In this case, a scan is required to be performed only over the view pyramid of the reference camera.

Cases 3 and 4: The two cases are symmetric. In both these cases, the scan area on the reference cylinder is larger than the view pyramid, but smaller than the whole cylinder.

Inverse mapping

Holes will be created by the forward mapping process if a small preimage area (i.e., on the reference panoramic image) is projected onto a larger screen area (i.e., on the virtual panoramic image), causing a loss of resolution. Holes may also occur because of the existence of regions that were not visible from any of the given cylindrical panoramic images. These regions have to be filled in order to produce a more visually appealing image. In this section, we shall discuss some techniques for filling in the holes.

Image smoothing

The simplest method for filling in the holes is to perform some kind of smoothing over the image space. The pixel value at a hole is determined by the pixel values of its neighbors. The value assigned is a weighted average of the neighbors which have been mapped in the forward mapping phase. The weights give more importance to the pixels that are closer to the hole than those that are farther away. The region of influence can be controlled and this offers a trade-off between the sharpness of the image and the number of holes that still remain after the image smoothing. A small kernel might tend to leave holes unfilled, while a large kernel might unnecessarily smooth out sharp edges.

Two image smoothing techniques involving circular interpolation kernels are implemented. The first uses a fixed radius while the other uses an adaptive radius. Both uses the weighting function

$$\omega(r) = 2^{-2\frac{r}{\sigma}}, r \leq 2\sigma \quad (1)$$

where r is the distance of the neighboring pixel to the pixel whose color is to be interpolated, and σ is the parameter indicating the size of the kernel. In the first technique, σ is set to 7 pixels. However, in the second technique, σ varies; at every pixel location, σ is automatically set to the distance of the central pixel to the nearest colored pixel. The second technique is very similar to the idea of elliptical weighted averaging described in [2], except that we apply a circular kernel in screen space on unfilled pixels only.

Geometric interpolation

An alternative method for screen space interpolation is the geometric interpolation. In this case, the interpolation is not performed over the pixel values, but rather over the geometric position of the pixel in the given images. The neighbors of the hole on the scan line and in the vertical line containing the pixel are inverse mapped onto the reference image. Bilinear interpolation is then performed on the quadrilateral in the reference image to obtain an estimate of the position of the pixel in the reference image that corresponds to the hole in the virtual image. This estimate is accurate if the scene area is small or if the scene is flat in this region and far from the camera optical center. The pixel value at this position is then mapped onto the hole.

Texturing issues

When multiple panoramic images are available, we can make use of the information from the different panoramic image pairs in order to obtain the virtual view. The forward mapping is done using every pair of cylindrical panoramic images available. Any image-smoothing technique can then be used for the inverse mapping as in the case of just two cylindrical panoramic images.

The geometric interpolation, however, has a new interpretation. There may be portions of the scene that are visible from the virtual camera position but are not visible from the reference camera position. This portion might be visible from some of the other given cylindrical panoramic images. Forward mapping can never map these regions onto the virtual cylinder if only pixels from the reference panoramic image are used. Even though the information is available from the other cylindrical views, a simple image smoothing technique will ignore the information. Application of the geometric interpolation technique only on the reference image will result in the mapping of some incorrect pixel value to the hole. If we can identify the cylindrical panoramic image from which the portion of the scene is actually seen, then a geometric interpolation performed on this panoramic image will yield a more accurate virtual panoramic image. Thus it is possible that we accurately recover the scene from the virtual viewpoint. Since we do not know the "right" cylindrical panoramic image on which to perform geometric interpolation, we perform geometric interpolation on all the cylindrical panoramic images available to us and average over the pixel values obtained from

each individual panoramic image. The averaging is actually weighted; a higher weight is accorded to pixels in the panoramic image whose camera center is closest to the virtual viewpoint. This is because we expect that the closer the virtual camera position is to a projection center of a real panoramic image, the more visually similar the virtual panoramic image is to that real panoramic image.

Experimental results

We ran our algorithms on a set of panoramic images, both synthetic and real. The size of the viewing image is 160×160. In general, we did not notice significant perceptual visual difference between the image smoothing technique using the interpolation kernel with adaptive circular radius and the geometric interpolation technique for the inverse mapping, as Figure 6 shows. There are significant differences in the rendered views between the all different techniques if close-up views (such as in Figure 6) are involved. For distant views, however, the results are hardly distinguishable. Overall, however, there is a reduction of quality in the reconstructed view using the image smoothing technique with fixed-radius interpolation kernel.

Some typical timing data collected are listed in Table 1. As can be seen, the rendering technique of forward mapping and geometric interpolation is the fastest amongst the three techniques using forward mapping as the first step. We have observed a significant variation in time between refresh. This can be attributed to the virtual view being a result of a varying number of projected preimage pixels, which in turn depends on the virtual camera field of view of the environment. Our program was run under the UNIX platform in DEC AlphaStation 600, which has an operating frequency of 333 MHz. Based on speed and output quality, the technique of forward mapping and geometric interpolation performed the best.

Mapping technique	t_{ave}	F
Forward mapping (FM) only	220 msec	4.5 Hz
FM & Fixed rad. smoothing	683 msec	1.5 Hz
FM & Adaptive rad. smoothing	1.15 sec	0.9 Hz
FM & Geometric interpolation	325 msec	3.1 Hz

Table 1: Timing comparisons between the different mapping techniques for motion within the vicinity of the virtual camera viewpoint shown in Figure 6. t_{ave} is the average time between refresh and F is the frequency.

When the number of the panoramic image sources used to generate a new view was increased, we noticed some degree of degradation in the quality and blurring of the picture, as can be seen in Figure 7. This is because of the slightly incorrect registration information that is a result of the spline-based registration technique. It is in general very difficult to achieve exact registration.

So far we have described how new views are generated at virtual camera locations within a cluster of panoramic images. We now describe how travel between clusters is implemented.

Moving between panoramic image clusters

Travel between wide scenes or clusters of panoramic images is implemented through transition points called "hotspots" located within the reference panoramic images. To illustrate how the idea of "hotspots" work, we use an example of a network of wide scenes represented by three clusters, each in turn, consisting of three panoramic images. One of the three clusters is shown in Figure 8. In this figure, the top three images are the panoramic images that represent the respective wide scene. The bottom left window is the top view of the 3-D distribution of precomputed points of the scene; crosses in the center of this window indicate the location of the camera centers corresponding to the three cylindrical panoramic images. The bottom right window is the viewing window. Note that the precomputed 3-D points shown in the bottom left window are not used in rendering the new views; they are there to provide a rough shape of the environment only.

Indicating "hotspots"

A "hotspot" can be viewed as a gateway from the current cluster to another cluster of panoramic images. From the user's point of view, it allows the viewer to move seamlessly from one scene to another scene. In our implementation, the user or developer indicates the "hotspots" and their auxiliary points as shown in Figure 9. Each "hotspot" is represented by hollow squares while each auxiliary point is represented by a cross. "Hotspots" comes in pairs, and for each pair, there is a designated source "hotspot" and a designated destination "hotspot." Figure 9 shows the pairs of "hotspots," where a source "hotspot" leads to a corresponding destination "hotspot" (in the direction of the arrowed line). The auxiliary points also come in pairs; they are used to compute the global affine motion from the source to the destination portions of the reference panoramic images.

Once the "hotspots" have been indicated and saved, the initialization for the cluster system is then complete. "Hotspots" are initialized by simply clicking at appropriate points in the reference panoramic images. The user can now virtually navigate this cluster system, i.e., he or she can move virtually navigate (in an unconstrained manner) within each cluster and travel smoothly (in a constrained manner) between clusters.

Moving to "hotspot" and changing scenes

We provide two ways of changing scenes via "hotspots." The first is to have the user manually navigate until he or she sees a "hotspot" within view; the "hotspot" is indicated by a hollow box. The user can then indicate a change of scene by clicking inside that box. The other way is to just type a key command. This has the effect of automatically moving and reorienting the virtual camera view such that the location of the virtual camera is at the reference location and the virtual camera is pointed directly at the nearest "hotspot." The camera motion is determined by linearly interpolating the camera position and angular orientation independently.

Once the virtual camera has been properly positioned and oriented, toward the "hotspot," transitioning between reference views of the source and destination clusters begins. The transition views are computed based on interpolated global affine motion. The global affine motion can be calculated from the corresponding the "hotspot" and auxiliary corresponding points by computing the least-squares best fit through Singular Value Decomposition (SVD). Let $(u_i, v_i)^{\mathrm{T}}$ and $(u_i', v_i')^{\mathrm{T}}$ be the ith point in the source image and the corresponding point in the destination image respectively. Then, using the global affine motion model,

$$\begin{pmatrix} u_i' \\ v_i' \\ 1 \end{pmatrix} = A \begin{pmatrix} u_i \\ v_i \\ 1 \end{pmatrix} = \begin{pmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} u_i \\ v_i \\ 1 \end{pmatrix} \tag{2}$$

For $N (N \geq 3)$ point pairs, the elements of A can be extracted by solving the overdetermined system through SVD [8].

Constructing intermediate views between clusters is done through inverse mapping, i.e., using the mapping from screen space to both source and destination image spaces. The color at each pixel is the weighted average of both the appropriately sampled pixels at the source and destination images. Let λ be the parameter ranging from 0 to 1 that indicates the "proximity" of the user to the destination scene (with 0 being at the current scene and 1 being at the destination scene). Then, if $\mathbf{c}$ is the color RGB vector,

$$\mathbf{c}_\lambda(\mathbf{u}) = \lambda \mathbf{c}_{\mathrm{src}}(\mathbf{f}(\mathbf{u}, \lambda, A^{-1})) + (1-\lambda)\mathbf{c}_{\mathrm{dest}}(\mathbf{f}(\mathbf{u}, \lambda, A)) \tag{3}$$

where

$$\mathbf{f}(\mathbf{u}, \lambda, A) = (I_{2\times 2} + \lambda(A_{2\times 2} - I_{2\times 2}))\,\mathbf{u} + \lambda \mathbf{t}, \tag{4}$$

with $I_{2\times 2}$ being the 2×2 identity matrix,

$$A_{2\times 2} = \begin{pmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{pmatrix}, \text{and } \mathbf{t} = \begin{pmatrix} a_{13} \\ a_{23} \end{pmatrix} \tag{5}$$

An example of automatically moving to a "hotspot," transitioning, and arriving at a new scene is shown in Figure 10.

Discussion

We chose our current approach of visualization using clusters of panoramic images rather than more densely sampled ones to reduce both computational and memory demands. Judicious choices of cluster location can enable us to visualize the complex scenes without sacrificing too much quality in the reconstructed virtual view and without prohibitively narrowing the range of virtual camera motion that results in view reconstruction with acceptable quality. However, our choice of approach opens up a range of questions.

Most of these questions relate to the quality of local navigation. In our work, we limit the number of panoramic images within each cluster to three. As such, the quality of reconstructed virtual views is sensitive to the quality of image registration between panoramic images within the cluster. Unless both the panoramic image construction and image registration are perfect, which is impossible in practice, the quality of reconstructed views is expected to degrade with increasing distance of the virtual camera position to the reference camera position. A reasonable solution to this is to restrict the range of motion of the virtual camera to within a certain distance from any of the panoramic image center. A distance threshold that can be used is the average baseline (i.e., average distance between camera centers) within the cluster.

As we have seen earlier, using multiple panoramic image sources does not necessarily result in higher quality view reconstruction than using just one panoramic image source. In theory, though, using multiple panoramic image sources should be better if the panoramic images are constructed and registered exactly correctly. In such as case, one can envision taking advantage of the multiple image sources to provide super-resolution images [3]. In practice, however, we are very likely better off using just one panoramic image source.

There is also the question of how many panoramic images per cluster is sufficient for acceptable output. While two panoramic images are theoretically sufficient for view reconstruction, the quality will be poor in the vicinity of the epipole locations, or points where the line joining the two camera centers intersect the cylindrical panoramic images. As a result, at least three panoramic images are required, as long as the camera centers associated with the images are not colinear. Again, there are the competing factors of high computational and memory demands against quality of reconstruction in choosing the number of panoramic images per cluster.

All said and done, our technique still requires some degree of manual intervention, specifically in specifying "hotspots," and subsequently their auxiliary points for estimation of global affine motion. This is necessary because panoramic images across clusters may differ substantially in appearance that automatic registration will fail. In addition, "hotspots," whose locations are *ad hoc*, are usually best left to the user or developer to specify. Currently, the placement of camera associated with each panoramic image within the cluster and the choice of the reference panoramic image per cluster are still heuristic.

Summary

We have described a technique for enabling smooth virtual navigation of a complicated network of wide scenes. Any environment that involves a large expanse of space (such as an outdoor environment) or significantly large occluding partitions (such as a multi-room environment within a floor of a building) is a good candidate for this method of visualization. The technique that we have proposed uses clusters of panoramic images, with each cluster representing a separate wide scene.

Each cluster of panoramic images allows local and unconstrained navigation within a wide scene. For this purpose, we have devised a combination of forward and inverse mapping techniques to reconstruct new virtual views using the original panoramic images. The interpolation technique using the adaptive circular radius yields the best results. The geometric interpolation technique yields images of very visually similar quality, except that it is significantly faster. It is a good tradeoff between the speed of view generation and quality of reconstruction.

Predefined "hotspots" provide gateways to smoothly transition (albeit in a restricted manner) from the current cluster to the next cluster. We interpolate views using global affine motion to simulate linear camera motion from one wide scene to another.

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References

[1] S.E. Chen. QuickTime VR – An image-based approach to virtual environment navigation. *Computer Graphics (SIGGRAPH'95)*, pages 29–38, Aug. 1995.

[2] N. Greene and P. Heckbert. Creating raster Omnimax images from multiple perspective views using the Elliptical Weighted Average filter. *IEEE Computer Graphics and Applications*, pages 21–27, June 1986.

[3] M. Irani and S. Peleg. Super resolution from image sequences. In *International Conference on Pattern Recognition*, pages 115–120, 1990.

[4] S. B. Kang and R. Szeliski. 3-D scene data recovery using omnidirectional multibaseline stereo. In *Proc.s IEEE Computer Society Conference on Computer Vision and Pattern Recognition*, pages 364–370, June 1996.

[5] R. Kumar, P. Anandan, M. Irani, J. Bergen, and K. Hanna. Representation of scenes from collections of images. In *IEEE Workshop on Representations of Visual Scenes*, pages 10–17, Cambridge, Massachusetts, June 1995.

[6] H. C. Longuet-Higgins. A computer algorithm for reconstructing a scene from two projections. *Nature*, 293:133–135, 1981.

[7] L. McMillan and G. Bishop. Plenoptic modeling: An image-based rendering system. *Computer Graphics (SIGGRAPH'95)*, pages 39–46, August 1995.

[8] W. H. Press, B. P. Flannery, S. A. Teukolsky, and W. T. Vetterling. *Numerical Recipes in C: The Art of Scientific Computing*. Cambridge University Press, Cambridge, England, 1988.

[9] H. S. Sawhney and S. Ayer. Compact representations of videos through dominant and multiple motion estimation. *IEEE Transactions on Pattern Analysis and Machine Intelligence*, 18(8):814–830, August 1996.

[10] R. Szeliski. Video mosaics for virtual environments. *IEEE Computer Graphics and Applications*, pages 22–30, March 1996.

[11] R. Szeliski and J. Coughlan. Hierarchical spline-based image registration. In *IEEE Computer Society Conference on Computer Vision and Pattern Recognition (CVPR'94)*, pages 194–201, Seattle, Washington, June 1994. IEEE Computer Society.

[12] R. Szeliski and H.-Y. Shum. Creating full view panoramic image mosaics and environment maps. *Computer Graphics (SIGGRAPH'97)*, pages 251–258, August 1997.

[13] J. Y. A. Wang and E. H. Adelson. Representing moving images with layers. *IEEE Transactions on Pattern Analysis and Machine Intelligence*, 3(5):625–638, September 1994.

[14] Y. Xiong and K. Turkowski. Creating image-based VR using a self-calibrating fisheye lens. In *Conference on Computer Vision and Pattern Recognition*, pages 237–243, San Juan, Puerto Rico, June 1997.

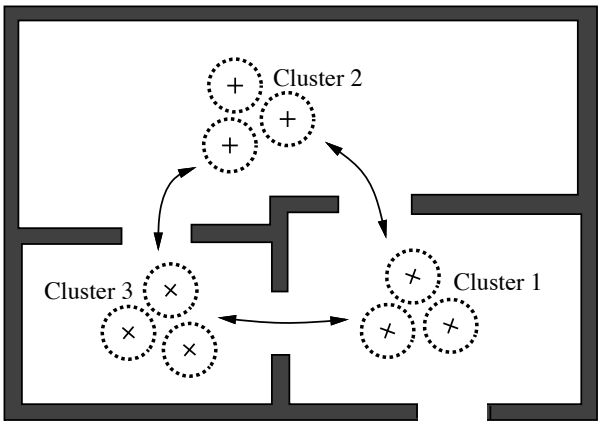


Figure 1: Virtual navigation using multiple panoramic clusters (3 clusters in this example). Here, each cluster consists of three cylindrical panoramic images.

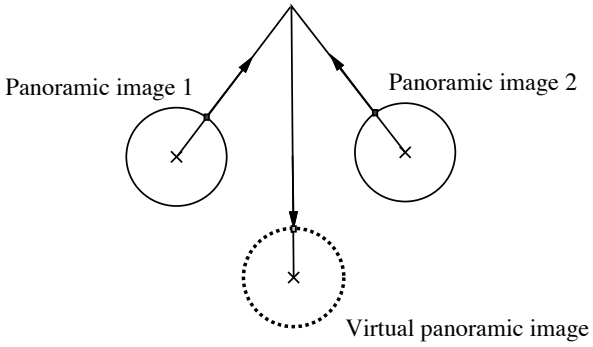


Figure 2: Forward mapping (within a cluster)

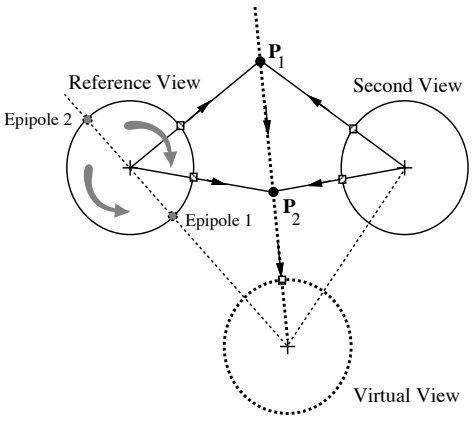


Figure 3: Handling occlusion using back-to-front ordering within a cluster (top view).

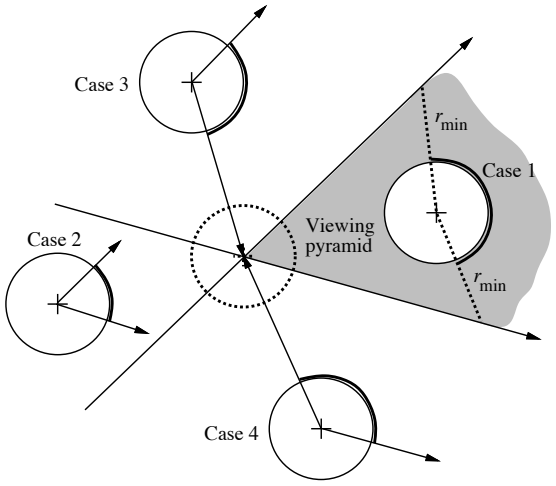


Figure 4: Different cases for forward mapping within a cluster (top view).

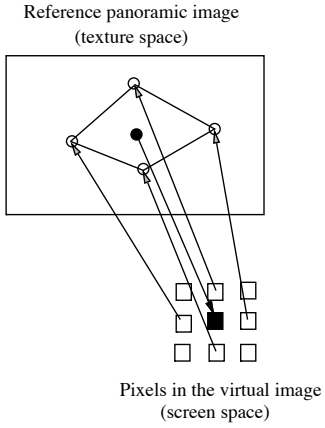
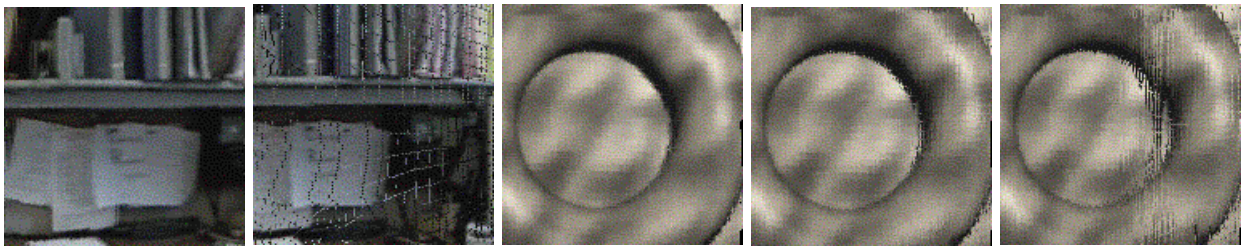


Figure 5: Geometric interpolation for filling in holes left by forward mapping.

(a) (b) (c) (d)

Figure 6: Results for a close-up view: (a) Forward mapping only, with the rest with forward mapping and (b) Smoothing with fixed radius, (c) Smoothing with adaptive radius, and (d) Geometric interpolation.



(a) (b) (c) (d) (e)

Figure 7: Using a single panoramic image source ((a), (c)), and some worst case effects of using multiple sources: two panoramic images ((b), (d)), and three panoramic images (e).

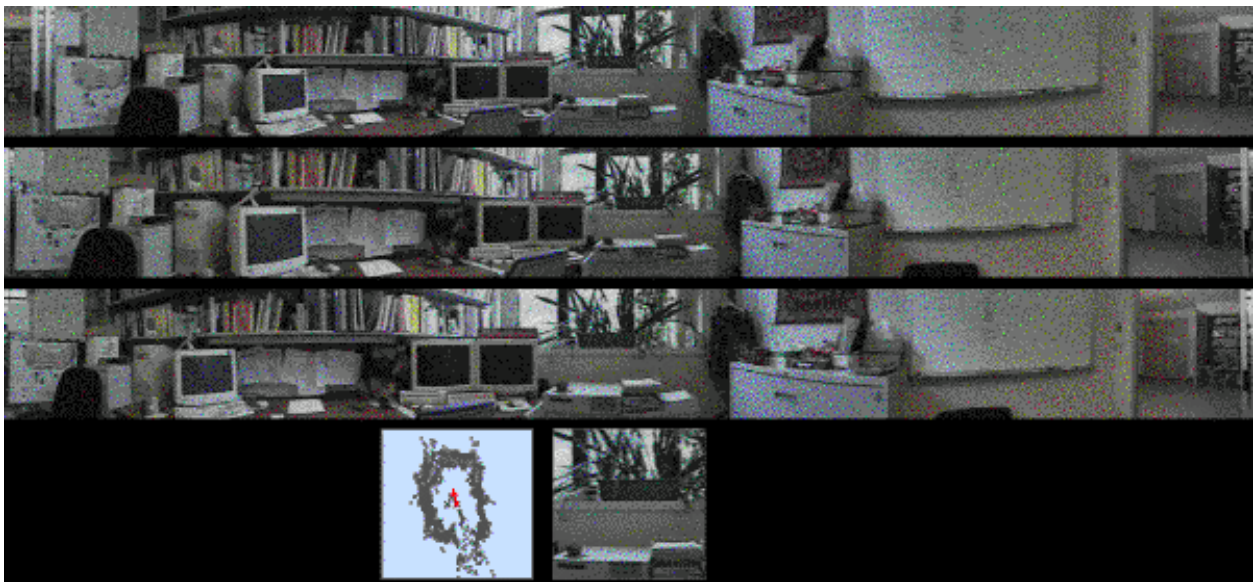


Figure 8: First cluster. See text for explanation of each image.

Figure 9: Example of "hotspots" (indicated by hollow squares) and supporting anchor points (indicated by crosses). The arrows indicate the direction of transition between panoramic clusters.

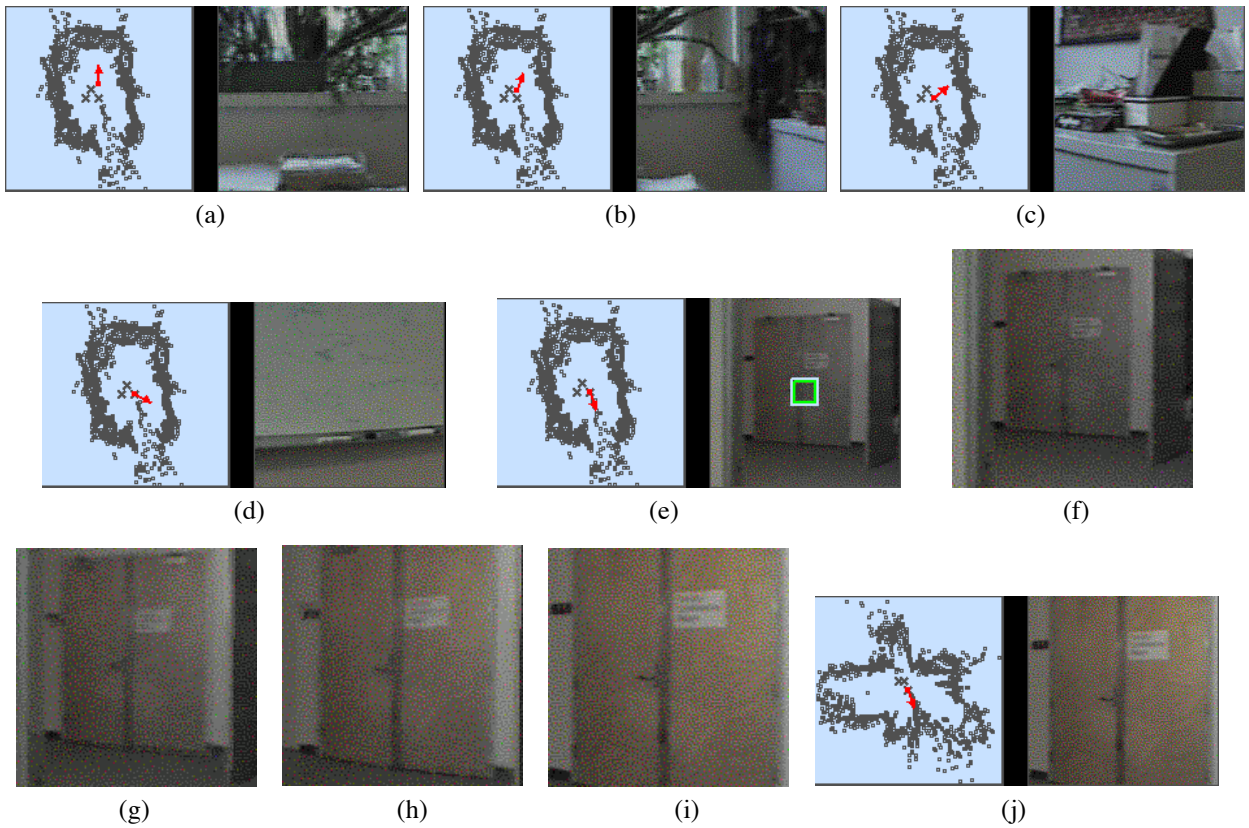


Figure 10: Sequence of snapshots taken during motion to one "hotspot" (a)-(e), transitioning from one cluster to another (f)-(i), and arrival at the destination cluster (j).