

# Stereo Panorama with a Single Camera \*

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## Abstract

*Full panoramic images, covering 360 degrees, can be created either by using panoramic cameras or by mosaicing together many regular images. Creating panoramic views in stereo, where one panorama is generated for the left eye, and another panorama is generated for the right eye is more problematic. Earlier attempts to mosaic images from a rotating pair of stereo cameras faced severe problems of parallax and of scale changes.*

*A new family of multiple viewpoint image projections, the Circular Projections, is developed. Two panoramic images taken using such projections can serve as a panoramic stereo pair. A system is described to generate a stereo panoramic image using circular projections from images or video taken by a single rotating camera. The system works in real-time on a PC. It should be noted that the stereo images are created without computation of 3D structure, and the depth effects are created only in the viewer's brain.*

## 1. Introduction

In this section short introductions are given to panoramic imaging, stereo panoramas, and manifold mosaicing. Sec. 2 discusses *Circular Projections*, the multiple viewpoint projections that can be used to create stereo panoramas. Sec. 3 describes the system to create stereo panoramas from a single rotating camera. Some geometrical properties are described in the appendix.

### 1.1. Panoramic Imaging

A panorama is an image having a wide field of view, up to a full 360 degrees. Panoramas can be captured or generated in several ways, among them:

- By using a single camera and a special lens or some kind of a mirror (conical, spherical, hyperboloidal, paraboloidal, etc.) [7, 8]. Through the mirror a single image can view the entire scene, or at least a very large field of view.
- By using multiple cameras, or one rotating camera, and stitching their images into a single panorama (also called “mosaicing”) [6, 12, 9].

It was a common belief that each panorama should have a single viewpoint, also called the “center of projection”. A panorama can be viewed as a projection of the scene onto a cylinder or a sphere through this viewpoint. It was necessary to have a single viewpoint panorama in order to create mathematically correct narrow field of view images from the panoramic image. In this paper we show one benefit of the deviation from the single viewpoint principle.

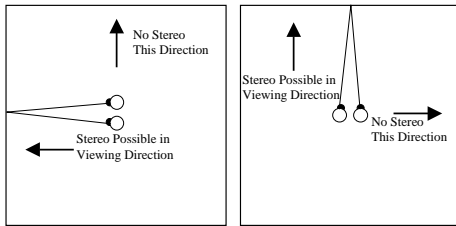
### 1.2. Stereo Panoramas

At first glance, creating panoramic stereoscopic images seems a contradiction. Pictures taken by ordinary cameras, and regular panoramic images, are taken from approximately a single viewpoint. A stereo pair is comprised of two images taken from two different viewpoints, corresponding to the locations of the two eyes. Two panoramic images, taken from two different viewpoints, can be viewed as a stereo pair in a direction perpendicular to the line connecting the two viewpoints. However, the two images will fail to give stereo perception when viewed in the direction of the line connecting the two viewpoints, since images from two cameras, one behind another, do not give stereo perception. See Fig. 1.

If a 3D model of a panoramic environment is given [4], two images could be rendered for every desired viewing direction. It was proposed in [3], for the first time, that two panoramic images are sufficient to generate stereo view in all directions. They suggested to rotate a stereo head with two cameras, and to create two panoramic mosaics, each corresponding to a different camera.

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**Figure 1. No arrangement of two single-viewpoint images can give stereo in all viewing directions. For upward viewing the two cameras should be separated horizontally, and for sideways viewing the two cameras should be separated vertically.**

In this paper we introduce and develop in detail a new type of multiple viewpoint image projections necessary for the creation of a panoramic stereo pair. We also show how these projections can be created by rotating a single camera, which is much more appropriate (and easy...) than using a pair of stereo cameras.

### 1.3. Manifold Mosaicing

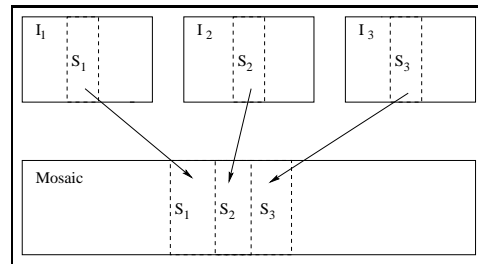
Most work on image mosaicing for panoramic views assumed that all images are taken from a single viewpoint, i.e., are only rotated about their optical center [6, 2, 12, 5]. Such images can be combined to create the entire viewing sphere (or cylinder) for their common viewpoint, and generate narrow field of view images of any desired direction.

Image mosaicing from a translating camera can not assume a single viewpoint. A system for creating a global view by pasting together columns taken by a translating camera comprising only of a vertical slit was proposed in [14]. The moving slit paradigm was implemented with image mosaicing in [9, 10]. In [11, 15] extensions were developed for cases of forward moving cameras, where it was shown that the strip should be bent to become perpendicular to the optical flow.

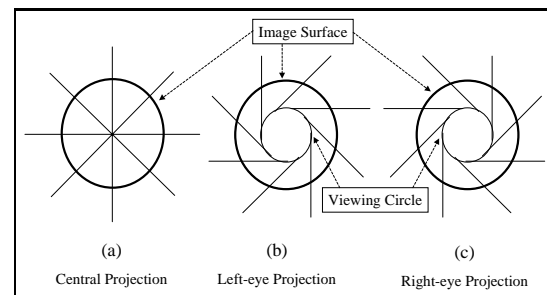
Fig. 2 shows how a panoramic mosaic is composed by pasting together strips taken from the center of the input images. The width of the strips depend on the displacement between the frames.

## 2. Multiple Viewpoint Projections

Regular images are created by a perspective projection: scene points are projected onto the image surface along projection lines passing through a single point, called the “optical center” or the “viewpoint”. Multiple viewpoint projections use different viewpoints for different viewing direction, and were used mostly for special mosaicing applications. Effects that can be created with mul-



**Figure 2. Manifold mosaicing is performed by pasting together strips taken from the centers of the input images.**

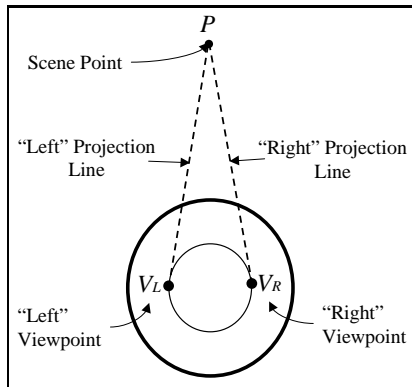


**Figure 3. Circular projections. Projection from the scene to the image surface is done along rays tangent to the viewing circle. (a) Projection lines perpendicular to the circular image surface create the traditional single viewpoint panorama. (b-c) Families of projection lines tangent to the inner viewing circle form the circular projections.**

multiple viewpoint projections and mosaicing are discussed in [13, 10]. Image-based projections using strips are described in [14, 9, 11, 15].

For stereo panorama we develop a special type of multiple viewpoint projections, *circular projections*, where both the left-eye image and the right-eye image share the *same* cylindrical image surface. To enable stereo perception, the left-eye and the right-eye are located on an inner circle (the “viewing circle”) inside the cylindrical image surface, as shown in Fig. 3. The viewing direction is on a line tangent to the viewing circle. The left-eye projection uses the rays on the tangent line in the clockwise direction of the circle, as in Fig. 3.b. The right-eye projection uses the rays in the counter clockwise direction as in Fig. 3.c. Every point on the viewing circle, therefore, defines both a viewpoint and a viewing direction of its own.

The applicability of circular projections to panoramic stereo is shown in Fig. 4. From this figure it is clear that



**Figure 4.** Viewing a scene point with “left-eye” and “right-eye” projections. The two viewpoints for these two projections are always in optimal positions for stereo viewing.

the two viewpoints associated with every scene point, using the “left-eye” projection and the “right-eye” projection, are in optimal relative positions for stereo viewing. This is true regardless of the direction of the observed point, unlike regular stereo pairs that have a preferred viewing direction.

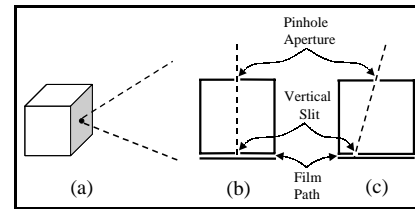
### 3. Single Camera Stereo Mosaicing

The generation of stereo panoramas will be explained using a model of a slit camera. It will then be described how a regular video camera can be used to create stereo panoramic images.

#### 3.1. Stereo Mosaicing with a Slit Camera

Images generated with circular projections for panoramic stereo can be photographed with a “slit camera” as shown in Fig 5. In such cameras the aperture is a regular pinhole as shown in Fig 5.a, but the film is covered except for a narrow vertical slit. The plane passing through the aperture and the slit determines a single viewing direction for the camera. The camera modeled in Fig 5.b has its slit fixed at the center, and the viewing direction is perpendicular to the image surface. The camera modeled in Fig 5.c has its slit fixed at the side, and the viewing direction is tilted from the perpendicular direction.

When a slit camera is rotated about a vertical axis passing through the line connecting the aperture and the slit, the resulting panoramic image has a single viewpoint (Fig 3.a). In particular, a single viewpoint panorama is obtained with rotations about the aperture. However, when the camera is rotated about a vertical axis directly behind the camera, and the vertical slit is not in the center, the resulting image has multiple viewpoints. The moving slit forms a cylindrical image surface. All projection lines, which are tilted from



**Figure 5.** Two models of slit cameras. (a) Side view. (b-c) Top view from inside the camera. While the camera is moving, the film is also moving in the film path. The locations of the aperture and the slit are fixed in each camera. (b) A vertical slit at the center gives a viewing direction perpendicular to the image surface. (c) A vertical slit at the side gives a viewing direction tilted from the perpendicular direction.

the cylindrical image surface, are tangent to some *viewing circle* on which all viewpoints are located. The slit camera in Fig. 5.c, for example, will generate the circular projection described in Fig. 3.b.

For stereo panoramas we use a camera having two slits: one slit on the right and one slit on the left. The slits, which move together with the camera, form a single cylindrical image surface just like a single slit. The two projections obtained on this shared cylindrical image surface are exactly the circular projections shown in Fig 3. Therefore, the two panoramic images, obtained by the two slits, enable stereo perception in all directions.

#### 3.2. Stereo Mosaicing with a Video Camera

Stereo panoramas can be created with video cameras in the same manner as with slit cameras, by using vertical image strips in place of the slits. The video camera is rotated about an axis behind the camera as shown in Fig 6. The panoramic image is composed by combining together narrow strips, which together approximate the desired circular projection on a cylindrical image surface.

In regular “manifold mosaicing”, as shown in Fig 2, each image contributes to the mosaic a strip taken from its center. The width of the strip is a function of the displacements between frames. Stereo mosaicing is very similar, but each image contributes **two** strips, as shown in Fig. 7. Two panoramas are constructed simultaneously. The left panorama is constructed from strips located at the right side of the images, giving the “left-eye” circular projection. The right panorama, likewise, is constructed from strips located at the left side of the images, giving the “right-eye” circular projection.

A schematic diagram of the process creating a pair of

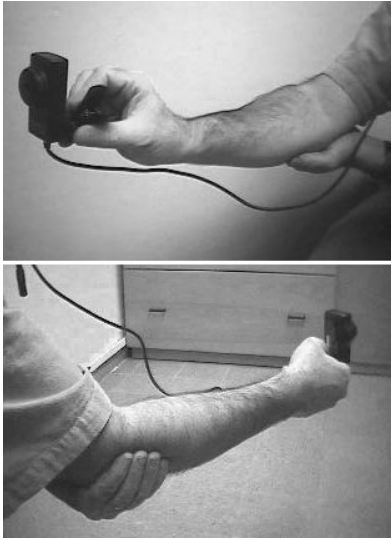


Figure 6. Two instances of the circular motion of the camera, rotating about the elbow.

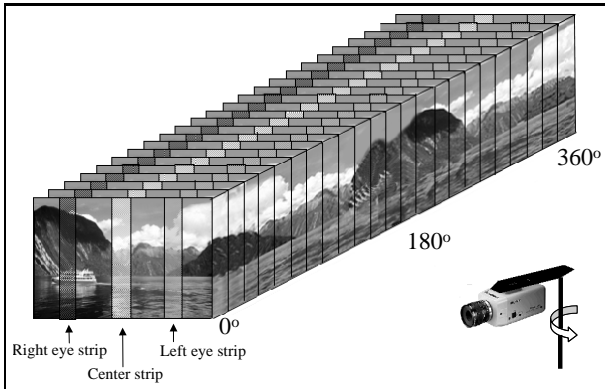


Figure 7. Stereo mosaics can be created using regular perspective images captured with a single video camera rotating about an axis behind the camera. Pasting together strips taken from each image approximates the panoramic image cylinder. When the strips are taken from the center of the images an ordinary panorama is obtained. When the strips are taken from the left side of each image, the viewing direction is tilted counter clockwise from the image surface, obtaining the right-eye panorama. When the strips are taken from the right side of each image, the left-eye panorama is obtained.

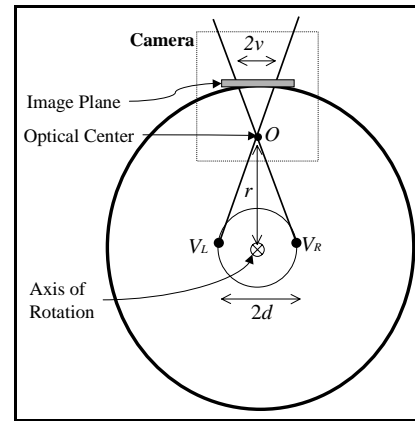
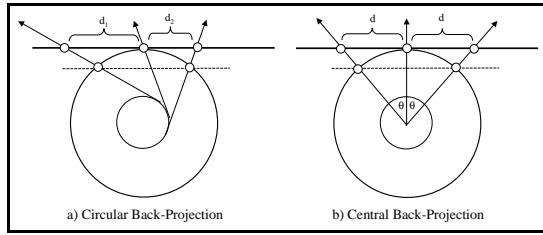


Figure 8. Schematic diagram of the system to create a pair of stereo panoramic images. A camera having an optical center “O” is rotated about an axis behind the camera. Note the “inverted” camera model, with image plane in front of the optical center.

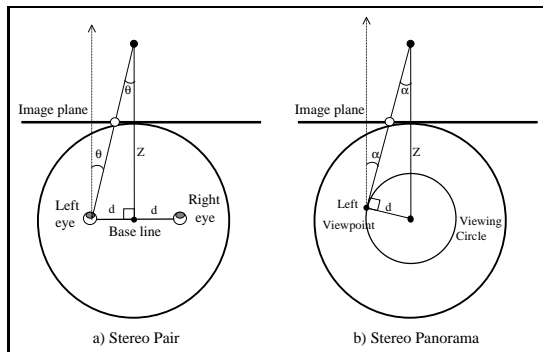
stereo panoramic images is shown in Fig 8. A camera having an optical center  $O$  and an image plane is rotated about an axis behind the camera. Strips at the left of the image are seen from viewpoints  $V_R$ , and strips at the right of the image are seen from viewpoints  $V_L$ . The distance between the two viewpoints is a function of the distance  $r$  between the rotation axis and the optical center, and the distance  $2v$  between the left and right strips. Increasing the distance between the two viewpoints, and thus increasing the stereo disparity, can be obtained by either increasing  $r$  or increasing  $v$ .

#### 4. Displaying Stereo Panoramas

Stereo panoramas, recorded on a cylindrical surface, can be naturally displayed on cylindrical surfaces as well. However, they can be viewed on more common planar surfaces such as flat screens, in which case the panoramic image should be projected from the cylinder onto a plane. While the cylindrical panoramic stereo images are created using circular projections (Fig. 3.b-c), they should be projected into the planar image surface using a central projection (Fig. 3.a). As seen in Fig. 9, central projections introduce fewer distortions, and are symmetrical for the left and right images. A central projection about the center of the cylinder, with the image plane tangent to the panoramic cylinder, is a natural projection; it is symmetric for the left side and the right side of the image as well as symmetric between the left-eye and right-eye projections. This projection also preserves the angular disparity that exists on the cylinder for a viewer located at the center of the cylin-



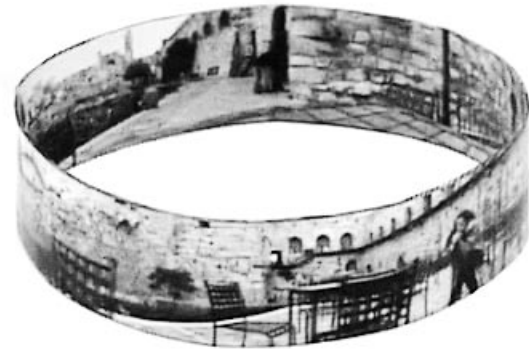
**Figure 9.** a) Projecting the cylindrical panorama using the original circular projection creates a distorted planar image. b) A central projection creates a symmetrical planar image which preserves the disparity for a viewer located at the center of the cylinder.



**Figure 10.** Comparing stereo panoramas and conventional stereo pairs. a) The disparity in conventional stereo is  $2\theta$  where  $\theta = \tan^{-1}(\frac{d}{Z})$ . b) The disparity in stereo panorama is  $2\alpha$  where  $\alpha = \sin^{-1}(\frac{d}{Z})$ . This disparity is preserved by the central projection of the panorama onto a planar image.

dical projection and hence preserves the depth perception.

Below is further examination of the process that generates the cylindrical panoramas using the multiple viewpoint circular projection, and creates planar images from the cylindrical panoramas using the single viewpoint central projection. Fig. 10 describes the relation between a conventional stereo pair and cylindrical panoramic stereo having the same base line of  $2d$ . For a point at depth  $Z$ , the disparity of conventional stereo is  $2\theta$ , where  $\theta = \tan^{-1}(\frac{d}{Z})$ . The disparity of stereo panorama is  $2\alpha$ , where  $\alpha = \sin^{-1}(\frac{d}{Z})$ . This disparity is preserved by the central projection of the panorama onto a planar image. Since the stereo disparities that can be fused by a human viewer are small,  $\sin(x) \approx \tan(x)$  and the disparities are practically the same.



**Figure 11.** Stereo panorama on a cylinder, created by rotating a single camera about a vertical axis behind the camera. Location: Tower of David, Jerusalem.

## 5. Examples

It is hard to present in a paper a 360 degrees stereo panorama. Since we can not supply a 360 degrees screen, or any sophisticated stereo viewing equipment, like polarizing glasses or head-mounted displays, we will display only a single stereo-pair which was cut out from a complete stereo cylinder.

Fig 11 shows a stereo panorama on a cylinder, created from a single rotating camera. Fig 12 shows a stereo pair projected from the stereo panoramic cylinder to a planar image surface for a narrow viewing direction.

## 6. Concluding Remarks

Multiple viewpoint scene-to-image projections, which enable the creation of stereo panoramic images, have been developed. based on these projections, a very simple system to create stereo panoramic images from a single rotating camera has been built. The same technology can also be used to create stereo panoramic images from a translating camera, e.g. an airplane flying over a terrain. Stereo panoramas can also be rendered from computer models using computer graphics methods.

## Appendix

### A. The Geometry of Stereo Panoramas

The following properties of stereo panoramas will be discussed in the appendix:

**Characteristics of virtual camera** as a function of the physical rotating camera and the strip stitching process.

**Alignment of left and right panoramas:** A constant shift is required to align the two panoramas such that points at infinity will have zero disparity.



Figure 12. A stereo pair generated from the cylinder shown in Fig. 11.

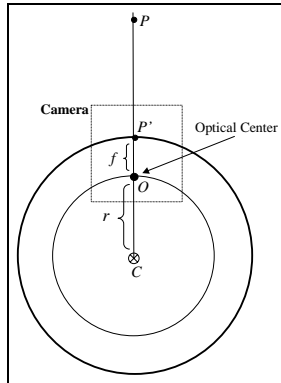


Figure 13. Rotating camera with center-slit projection.

**Relation between depth and parallax:** Parallax is a function of the camera characteristics and the depth. Control of camera characteristics is necessary in order to get parallax within the fusion disparity of the human eye.

#### A.1. Characteristics of Virtual Camera

Fig. 13 illustrates the creation of a panorama using a rotating camera with a slit located exactly in the middle. Point  $C$  is the center of rotation,  $r$  is the distance between  $C$  and the optical center  $O$  of the physical camera, and  $f$  is the focal length of the physical camera. A point  $P$  in the world is projected into the point  $P'$  on the cylindrical image. This setup defines a virtual camera called the *reference camera* which has the following properties:

1. A single center of projection located at  $C$ .

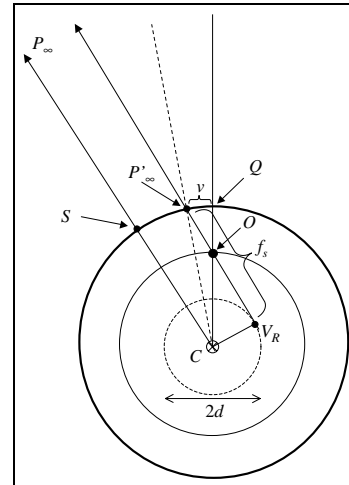
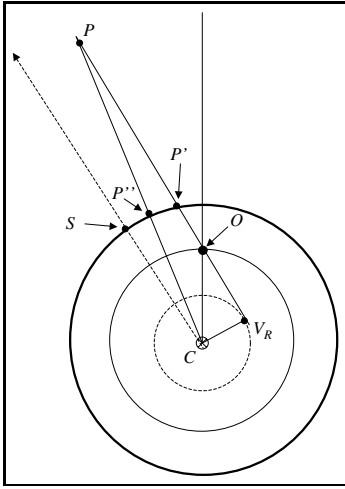


Figure 14. Rotating camera with left-slit projection: a point at infinity.

2. Focal length  $f_v = r + f$ .  $f_v$  is also the radius of the cylindrical projection.

Fig. 14 illustrates left-slit projection (for the right eye). A point  $P_\infty$  is projected on the image plane (and the image cylinder) at point  $P'_\infty$ . The slit is located at distance  $v$  to the left of the center of the camera. The virtual camera in this case has the following properties:

1. Multiple centers of projection located on a circle centered at  $C$  with radius  $d$ .
2. Effective focal length  $f_s$ .



**Figure 15. Rotating camera with left-slit projection for point at depth  $Z$ .**

### A.2. Panorama Alignment (Vergence)

Fig. 14 illustrates the projection of point  $P_\infty$  located at infinity by the reference camera into point  $S$ , and by the left-slit camera into  $P'_\infty$ . The angle  $\beta$  between these points is the misalignment of the left-slit camera relative to the reference camera.  $\beta = \angle(SCP'_\infty) = \angle(CP'_\infty V_R) = \sin^{-1} d/(r + f)$  where  $d = r \cos \alpha$ ,  $\alpha = \tan^{-1} v/f$ . For vergence on points at infinity, such that they will be aligned in both panoramas, the left panorama and the right panorama should each be rotated towards the reference camera by  $\beta$ .

### A.3. Relation Between Depth and Parallax

Fig. 15 illustrates the projection of point  $P$  located at depth  $Z$  (relative to the reference camera) by the reference camera into point  $P''$  and by the left-slit camera into  $P'$ . The gap between  $P''$  and  $S$  is the (negative sign) parallax of point  $P$  after vergence on infinity.  $Parallax = \angle(SCP'') = \angle(CPV_R) = \sin^{-1}(d/Z)$ . Relative rotation of the panoramas can therefore create vergence on any desired depth.

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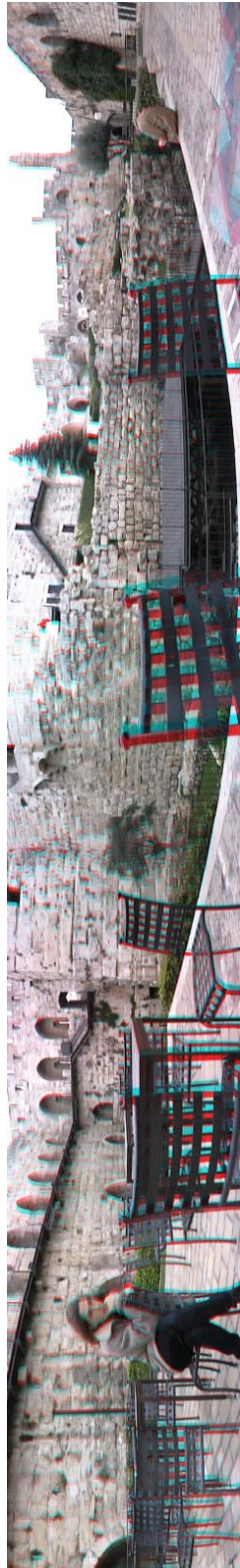


Figure 9. Stereo Panoramas generated by a single rotating camera scanning the scene. For stereo sensation, view with red-blue anaglyph stereo filters. *This figure does not appear in the CVPR'99 proceedings!*