Rectified Mosaicing: Mosaics without the Curl*

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Abstract

When images captured by a tilted camera are mosaiced into a panorama, the resulting mosaic is curled. This happens, for example, with a panning camera that is not perfectly horizontal, and with a translating camera facing a tilted planar surface. The tilt of the camera causes differences in image velocity between the top and bottom parts of the image, causing the curled mosaic. In rectified mosaicing these distortions are overcome by warping the strips into rectangles, while keeping some image feature invariant. This warping equalizes the image motion at the different image parts, and the resulting mosaic is straight. Mosaicing is done without camera calibration or knowledge of the scene, and the process adapts automatically to smooth changes in the scene and the imaging conditions.

1 Introduction

Everyone who tried to use mosaicing is familiar with the curling of the mosaic as shown in Fig. 1. This curl happens, for example, when the camera is rotated about a vertical axis, and the camera is not perfectly horizontal. It also happens when a translating camera is viewing a planar surface in a tilted direction. In this paper we review the reasons for this distortion, and propose an algorithm to create straight mosaics even when ordinary mosaicing methods create curled mosaics.

Some mosaicing techniques map the images onto a cylinder or a sphere [4, 9, 5]. These methods work for a rotating camera, and assume knowledge about the internal parameters of the camera. Other methods [3] perform the mosaicing by warping all the images onto a plane, usually the image plane of one of the input images (the "reference plane"). These methods assume some global parametric model over the entire image, and may create distorted mosaics as described in Section 2.

Figure 1. A curled mosaic constructed by Manifold Mosaicing. The panning camera was slightly tilted upwards.

1.1 Manifold Mosaicing

Manifold Mosaicing [10, 6] enables mosaicing of both a rotating camera and a translating camera without the need to know in advance the camera motion and internal parameters. The algorithm constructs the mosaic by pasting strips taken from the original images, and the mosaic surface (manifold) is created automatically. The strip collection process follows the *Linear Pushbroom Camera* model [2]. With horizontal camera motion the mosaic is a collection of vertical scan lines, each scan line formed by perspective projection. The scene to image projection of the camera in this case is perspective in the vertical direction and parallel in the horizontal direction. A diagram of this mosaicing appears in Fig. 2.

The implementations of manifold mosaicing proposed in [10, 6] perform well when the camera is rotating or translating horizontally, but may fail when there are scale changes in the image, and when there are motion differences due to parallax and camera tilt. Applicable solutions for the cases of zoom and forward motion were proposed in [8, 7, 11]. In this approach strips can be of more general shapes, and local warping of the strips can prevent the global shrinking (or expansion) associated with the mosaicing of zooming

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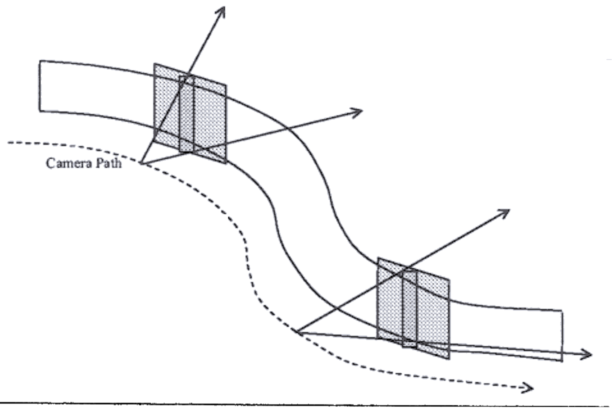

Figure 2. Manifold Mosaicing. The mosaic is created by collecting strips from images taken by a moving camera.

images. Still, these methods assume that the motion magnitude across the strips is approximately uniform.

Rectified mosaicing is a new generalization of manifold mosaicing for cases in which the motion magnitude is not uniform. The algorithm warps the strips onto the mosaic image such that the image motion becomes approximately parallel and of equal magnitude. It can be interpreted as an approximation of the image which would have been created by a pushbroom camera undergoing the same motion as in the input sequence.

Rectified mosaicing is demonstrated for the case of a tilted panning camera, as well as the case of a tilted camera translating in a planar scene. It is also shown that the same concept can be used for mosaicing from a camera translating forward in a tunnel or in a pipe.

2 Rectified Mosaicing

As in manifold mosaicing, rectified mosaicing builds the mosaic from a collection of strips taken from the original images. The case of a translating camera and a planar scene will be initially presented, but similar principles can be used for other scenes and for camera rotation.

Consider the case of a camera translating to the right in front of a planar scene, with the viewing direction tilted up and to the right from a perpendicular view. Were the plane covered with equidistant horizontal and vertical lines, each image of this plane would look similar to Fig. 3.a. Parallel lines on the plane are not parallel in the image, and a square in the plane is projected onto a general quadrangle in the image. The image motion between consecutive images is similar to the one in Fig. 3.a. Mosaicing the images by aligning and warping them to one of the input images gives a distorted mosaic as shown in Fig. 3.b. This distortion results from the need to shrink and rotate each image

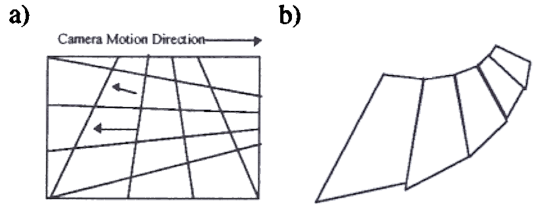

Figure 3. Tilted camera moving horizontally and viewing a planar scene.
a. The image of parallel vertical and horizontal lines in the scene.
b. Mosaicing images warped to align with the first frame gives a distorted mosaic.

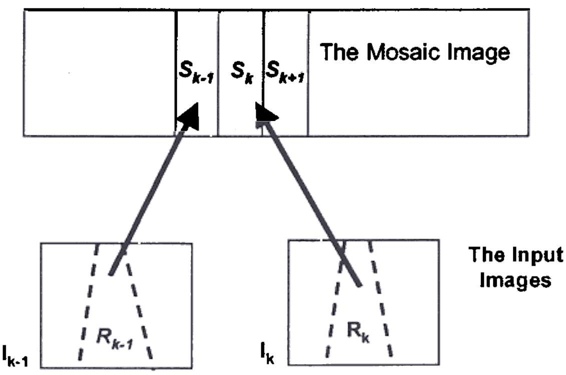

Figure 4. Warping non-rectangular image regions R_k to rectangular strips S_k in the mosaic.

to align with the previous image. Manifold mosaicing [6], which does not scale strips, results in a curved mosaic as in Fig. 7 and Fig. 1.

To avoid the curling distortions, the input images can be warped such that rectangular regions in the scene are mapped to rectangular regions in the mosaic. For example, if the borders of the image strips in Fig. 4 are projections of parallel lines in the world, these strips should be mapped to rectangular strips in the mosaic. As a result of such warping the optical flow inside the strip becomes approximately parallel and of equal magnitude.

The three main stages in rectified mosaicing are summarized bellow, and will be described in detail in the coming sections:

1. *Motion computation* - compute the motion between every pair of successive images in the sequence. For a planar scene, as well as for a rotating camera in any scene, the eight parameters of the planar-projective

(homography) motion is computed [1].

2. *Determine the image strips to be warped into the mosaic, and the anchor.* In rectified mosaicing each image always has some feature, the *anchor*, which remains invariant under the warping of the strip. The invariance of the anchor prevents global rescaling. In the case of a sideways moving camera, the anchor can be a vertical image column.

3. *Determine the size and location of the strips in the mosaic.* The vertical location of the strip in the mosaic changes according to the vertical image motion. The width of the strip is determined by the horizontal image motion. In case of uniform image translation this width is the frame to frame translation. There are several options when different translations occur at different parts of the strip.

   One option as shown in Fig. 4 is to set the width of the mosaic strip, S_k, as the widest part of the image strip R_k. In this case regions are never shrunk, and information is preserved in the resampling process.

2.1 Non Symmetrical Strips

This section describes one approach for rectified mosaicing. It is shown how to select the borders of the polygonal regions in the input images (Fig. 5), and how to warp these regions to strips in the mosaic image. The image motion is assumed to be from left to right, and the anchor is the left border of the region. The intersection of the anchor with the top and bottom image borders is marked by P_k and Q_k. Given the homography H_k between Image I_k and Image I_{k+1}, let $\tilde{Q}_k = H_k^{-1}(Q_{k+1})$ and $\tilde{P}_k = H_k^{-1}(P_{k+1})$. $\tilde{Q}_k$ and $\tilde{P}_k$ are the mapping onto Image I_k of the anchor edges in Image I_{k+1}.

Let L_k be the line passing through $\tilde{Q}_k$ and $\tilde{P}_k$. We find on the line L_k two points Q'_k and P'_k such that their distance is like the distance between $\tilde{Q}_k$ and $\tilde{P}_k$, and their centroid is on the middle row of the image. The region in the image to be warped to a strip in the mosaic is defined by the quadrangle $\tilde{Q}_k \tilde{P}_k P_k Q_k$. The warping is done by smooth (e.g. bilinear) interpolation of the coordinates of $\tilde{Q}_k, \tilde{P}_k, P_k, Q_k$. The use of an interpolation is needed for strip alignment, and this is an approximation to the real transformation which is unknown. As the strips are very narrow, this approximation is satisfying.

The next strip in the mosaic is placed with vertical offset of $\| \tilde{Q}_k - Q'_k \|_2 * \frac{h}{\|Q'_k - P'_k\|_2}$ from the current strip, where h is the image height.

This method can be easily adapted to a vertical motion and to forward motion.

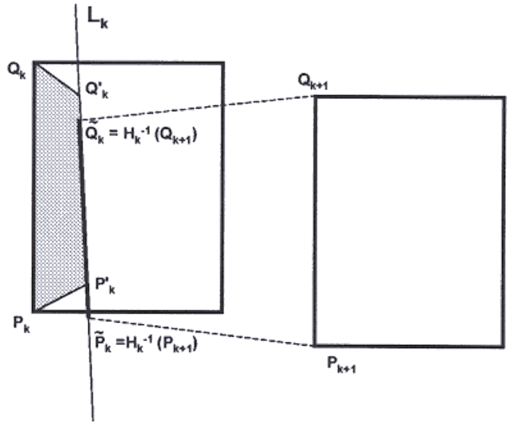

Figure 5. Non symmetric strip. The anchor is the left border of the strip.

2.2 Symmetrical Strips

This section describes an alternative approach for rectified mosaicing, under the same imaging conditions as in Sect. 2.1. In this section the strips are taken symmetrically around the center of the frame.

We mark the vertical line at the center of the image as C_k, and its intersection with the top and bottom image borders by P_k and Q_k. We would like to choose a region which is approximately symmetrical around C_k, to reduce lens distortion. (This is the reason for choosing C_k as the anchor). This region is illustrated in Fig. 6

Given the homography H_{k-1} between Image I_k and Image I_{k-1}, Let O_{k-1} be the center of image I_{k-1}, and let d be the vertical offset between O_{k-1} and $H_{k-1}(O_{k-1})$. Let P'_k be a point vertically shifted from P_k by d, and Let Q'_k be a point vertically shifted from Q_k by d. Based on the homography H_k between Image I_{k+1} and Image I_k, we apply a similar process between images I_k and I_{k+1}.

We now use the homographies to map points P'_{k+1} and Q'_{k+1} from Image I_{k+1}, and points P_{k-1} and Q_{k-1} from Image I_{k-1}, to Image I_k. We then find the middle points: Let F_L be the homography mapping an arbitrary rectangle UVWX to the points $H_{k-1}(P_{k-1}), P'_k, Q'_k, H_{k-1}(Q_{k-1})$ respectively, and Let F_R be the homography mapping U-VWX to the points $P_k, H_k^{-1}(P'_{k+1}), H_k^{-1}(Q'_{k+1}), Q_k$ respectively. The region borders are defined by:

$$A_{11} = F_L(\frac{U+V}{2}), A_{12} = F_R(\frac{U+V}{2}),$$

$$A_{21} = F_L(\frac{W+X}{2}), A_{22} = F_R(\frac{W+X}{2})$$

The polygonal region in the image is comprised of two quadrangles: the left quadrangle, with the corners at P'_k,

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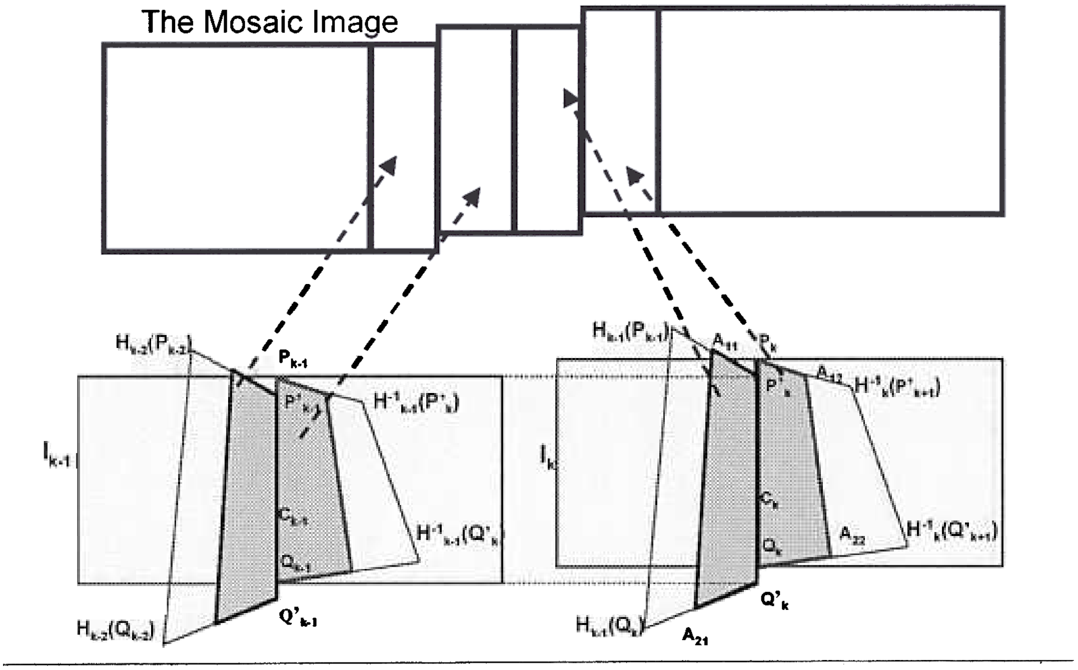

Figure 6. Mosaicing with symmetrical strips. Two trapezoids in the image are mapped to two rectangles in the mosaic.

Q'_k, A_{11}, and A_{21}, and the right quadrangle, with the corners at P_k, Q_k, A_{12}, and A_{22}. Each of these quadrangles is mapped to a rectangle in the mosaic. We warp the left quadrangle to a rectangle in the mosaic by some smooth (e.g. bilinear) interpolation of the coordinates of the corners like in the asymmetric case. We apply a similar process to the right part of the strip (rectangle) and the right part of the region.

We place the left part of the strip at the same vertical offset as the right part of the previous strip, and the right side of the strip with vertical offset of d from the left part.

3 Geometrical Interpretation

The implementation of rectified mosaicing for a planar scene is an approximation to the image which would have been created by a pushbroom camera.

The anchors are placed in parallel along the mosaic, completing a parallel projection in the direction of the motion of the camera. Assuming the motion between successive frames is small, canceling the parallax by some smooth interpolation of the coordinates is a satisfying approximation for the narrow gaps between the anchors. This is equivalent to projecting regions from the input images to some dynamic manifold which is extrusion of a line segment as in [6].

Similarly, for the case of pure rotation about an arbitrary axis, the constructed mosaic is equivalent to projection of the images onto a cylinder, even when the camera is tilted.

Rectified mosaicing is a generalization of manifold mosaicing [10, 6] and pipe mosaicing [8, 7, 11]. In manifold mosaicing the camera is panning or translating aside, the manifold is an extrusion of a line, and the anchor is a line. In pipe mosaicing, the camera is moving forward or zooming, the manifold is a Pipe, and the anchor is an elliptic curve. In both cases the manifold shape is determined only by the camera motion.

In rectified mosaicing the manifold is determined by the shape of the *chosen* anchor. By having some rough knowledge of the scene geometry, a manifold can be chosen which is generally similar to the scene. For example, a vertical version of the method described in 2.1 can be used for a sequence taken by a camera moving forward over a plane. In this case the images will be projected to horizontal manifold, rather than a pipe.

4 Results

We tested *Rectified Mosaicing* with a translating camera and a planar scene. As reference, we compared the result to an implementation of manifold mosaicing, as described in [6]. Fig. 7 shows a mosaic of a slanted plane created by manifold mosaicing. Although the motion between the images cannot be modeled by a 2D rotation and translation,

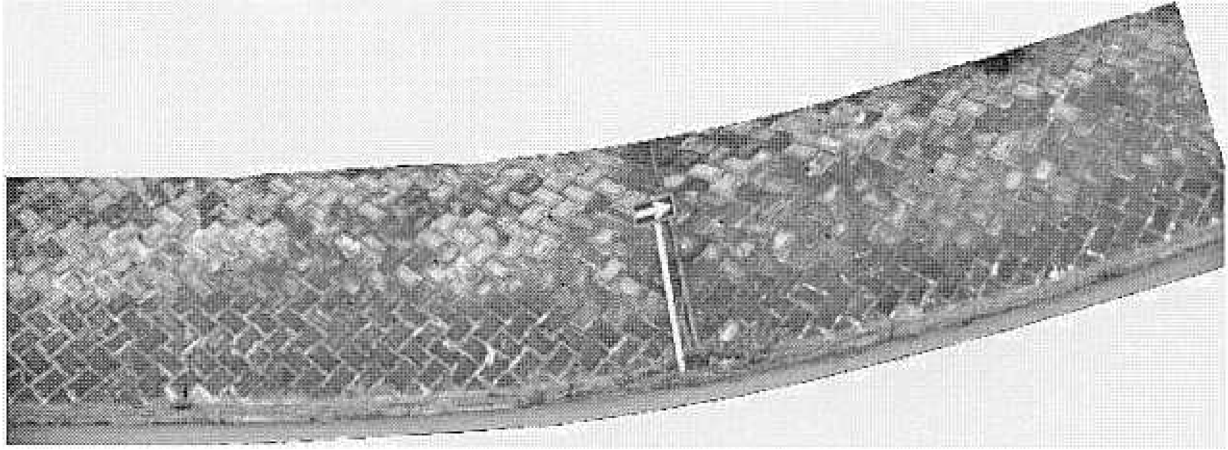

Figure 7. Mosaicing a slanted wall using manifold mosaicing. Resulting mosaic is curled.

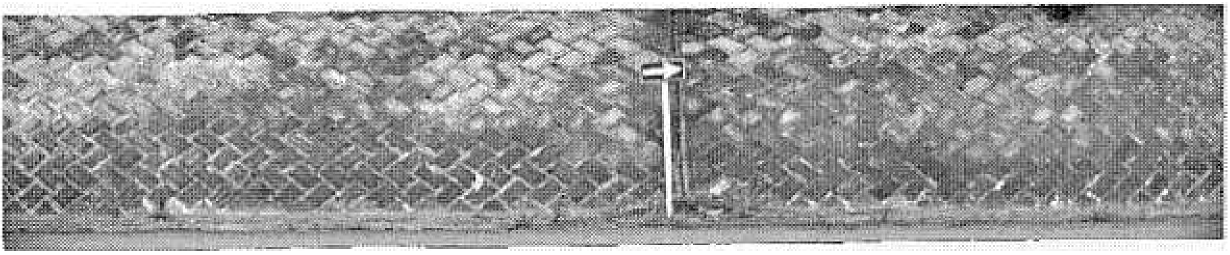

Figure 8. Mosaicing a slanted wall using rectified mosaicing. Resulting mosaic is straight

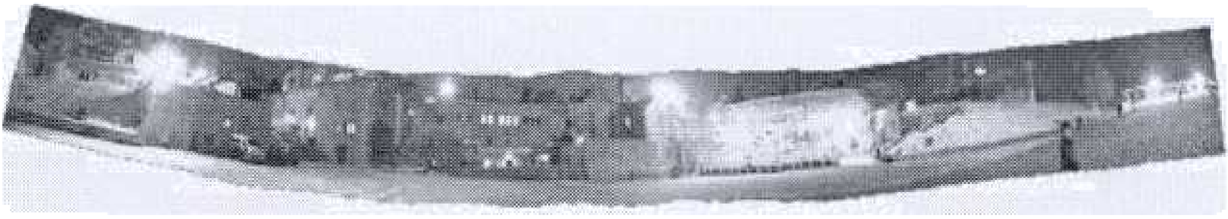

Figure 9. Mosaicing from a panning camera which is slightly tilted, using manifold mosaicing. Resulting mosaic is curled.

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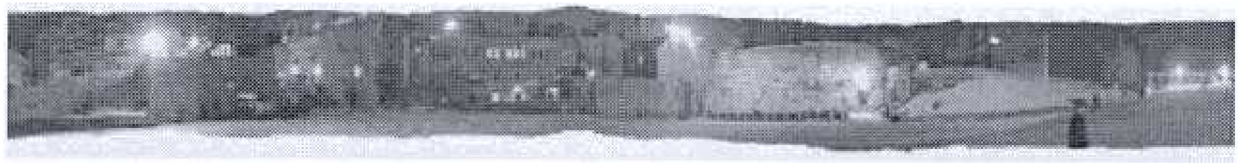

Figure 10. Mosaicing from a panning camera which is slightly tilted, using rectified mosaicing. Resulting mosaic is generally straight, following the motion of the camera.

the manifold Mosaicing program succeeded to create a mosaic, compensating for the bad alignment model by erroneous approximation of the rotation of the camera about the Z axis. The result is a curled mosaic image. Similar phenomenon happens when trying to create a mosaic from a sequence taken by a tilted rotating camera (Fig. 9). Applying the rectified mosaicing gives better results: The mosaic is generally horizontal, following the motion of the camera. This is demonstrated in Fig. 8 and Fig. 10.

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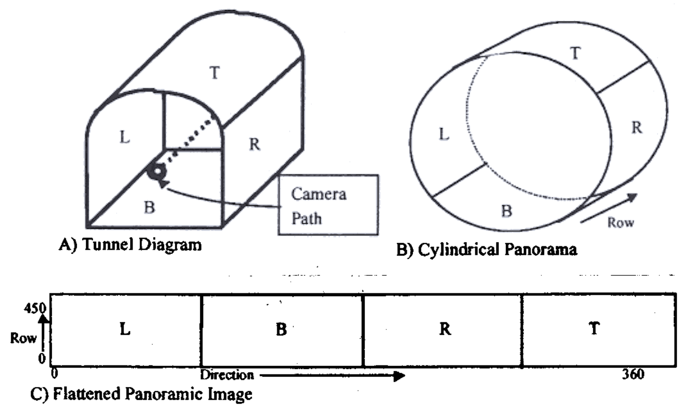

er, it is necessary to equalize the panoramic image (stretch along columns) such that a strip with parallel (and straight) boundaries could be taken from the image to be placed in the mosaic. This can be done by expanding each image column (in the direction of motion) by the ratio between the motion in this column and the motion of the column having largest motion. (Alternatively, a fixed column may be designated as a reference). During such normalization one row is designated as the "fixed" *anchor*, i.e. unaffected by the normalization. This row can be, for example, the central row in the mosaic image. After such normalization, a cylindrical strip can be taken from the panoramic image for placement in the mosaic. The result mosaic is a very long cylinder, as illustrated in Fig. 12.

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Figure 12. Mosaicing with a Moving Panoramic Camera. Each image includes a panorama around the direction of motion.

6 Conclusions

Rectified mosaicing is a framework for mosaicing image sequences taken from a translating or a rotating camera. An ideal pushbroom camera would be best for mosaicing under the most general conditions, and rectified mosaics are approximations to the images of a pushbroom camera. Rectified mosaics are obtained by warping the image strips to compensate for the parallax. In the case of a camera rotating about an arbitrary axis, rectified mosaicing maps the images onto a cylinder, without the need for calibration of the camera. In the case of a camera translating in front of a tilted plane, a frontal multi-perspective image of the plane is obtained.

Rectified mosaicing is based on motion computation between pairs of images, and thus it is adaptive to smooth changes in the scene geometry and in the camera motion. Unlike previous mosaicing methods, this framework provides some freedom to choose the kind of manifold on which the input images are projected. We use rough knowledge of the scene geometry to select the appropriate manifold for each scene.

We have demonstrated in this paper implementation of *Rectified Mosaicing* for several cases, including translation in a planar scene and in a tunnel. The same principle can be used for mosaicing of more general smooth scenes, assuming the optical flow between consecutive images can be computed.

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