Using Vanishing Points To Correct Camera Rotation In Images

Andrew C. Gallagher
Eastman Kodak Company
andrew.gallagher@kodak.com

Abstract

Vanishing points provide valuable information regarding the camera model used to capture an image. To explore the relationship between classes of camera models and the location of vanishing points, typical consumer photographic behavior is considered. Based on these findings, an algorithm is presented that can automatically remove the tilted appearance of an image captured with a camera rotated about the principal axis. The algorithm includes detecting vanishing points in an image, determining if any vanishing points are associated with vertical lines in the scene, computing the angle of rotation, and rotating the image. Results of the algorithm are shown for a set of images. The algorithm performs well and produces pleasing images from original images that contain undesirable levels of tilt.

1. Introduction

It is well understood that the projection of a three-dimensional world onto a two-dimensional image results in the convergence of parallel world lines at a vanishing point in an image. The locations of vanishing points in the image provide a wealth of information about the camera. For example, the focal length of the camera can be calculated from two vanishing points associated with orthogonal scene directions [7]. Furthermore, the orthocenter of the triangle formed by three vanishing points associated with three orthogonal scene directions is the principle point [2]. Likewise, those same three vanishing points can be used to determine both the internal camera parameters (under certain simplifying assumptions) and camera rotation [3].

Even a single vanishing point can provide valuable information about the camera model. In turn, this information can be used to improve the composition of the image.

The location of vanishing points in the image plane conveys a great deal of information describing the position of the camera relative to the scene. This paper shows that vanishing point location can be used to determine the rotation of the camera about the principle axis. A camera positioned in such manner often results in an aesthetically unattractive image that appears to be tilted, as shown in Figure 6. A tilt as small as $|\beta| = 2°$ can negatively affect the visual composition of an image.

In some cases, a tilted camera position is consciously chosen by the photographer for purposes of composition. However, in many cases, this tilted position is unintentional and can result in an image with the aforementioned undesirable tilted appearance. This occurs because the camera is difficult to hold steady, especially in the case of small, lightweight cameras. It can also be caused also from the rotational inertia associated with depressing the shutter button.

Humans tend to prefer images where the horizon is level rather than tilted. In the world of art, where the artist has full control of the rendering of a world scene, it is common practice to begin drawing by laying out perspective with a horizontal horizon [9]. This ensures that the completed work will not appear as if it were tilted or rotated. A digital image captured with a camera rotated about the principal axis can be improved by rotating the image by the proper angle to remove the appearance of tilt.

2. The camera model

Using homogeneous coordinates, the projection of a scene point to the image is described by the equation:

$$\mathbf{x} = \mathbf{P}\mathbf{X} \tag{1}$$

where $\mathbf{P}$ is the camera model, $\mathbf{X}$ is a world point, and $\mathbf{x}$ is the corresponding image point.

The camera model $\mathbf{P}$ describes the relationship between the scene coordinate system and the image coordinate system as well as the internal camera parameters.

The camera model [6] can be written as

$$\mathbf{P} = \mathbf{K}[\mathbf{R}|\mathbf{T}] \tag{2}$$

where:

$\mathbf{K}$ is a 3 x 3 matrix describing the internal camera parameters.

$\mathbf{R}$ is a 3 x 3 matrix describing the rotational mapping from the world coordinate frame into the camera coordinate frame.

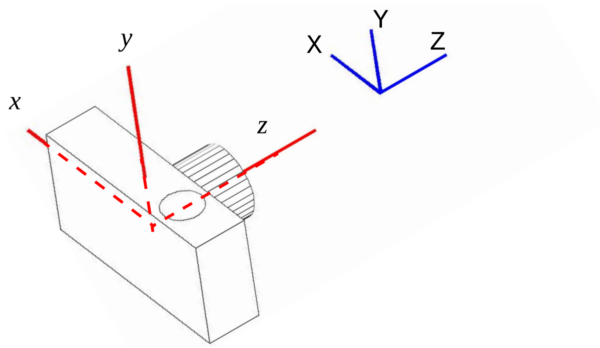

Figure 1: The geometry of the camera coordinate frame and the world coordinate frame for the default case.

T is a 3 x 1 vector that describes the translational mapping from the world coordinate frame into the camera coordinate frame.

The vanishing points of the world coordinate directions are the columns of the matrix **V** and are found by determining the mapping of points at infinity along the axes' directions:

$$\mathbf{V} = \begin{bmatrix} \mathbf{v_x} & \mathbf{v_y} & \mathbf{v_z} \end{bmatrix} = \mathbf{P} \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \\ 0 & 0 & 0 \end{bmatrix} = \mathbf{KR} \tag{3}$$

For simplicity, we assume the camera has no skew, has square pixels, and the principle point has assigned coordinate $[0\ 0\ 1]^T$. The matrix **K** reduces to:

$$\mathbf{K} = \begin{bmatrix} \alpha & 0 & 0 \\ 0 & \alpha & 0 \\ 0 & 0 & 1 \end{bmatrix} \tag{4}$$

where α is the focal length of the system in pixels.

3. The world coordinate frame

The world coordinate system is given a specific natural assignment. The XZ-plane is parallel to the ground plane and the Y-axis is parallel (but the negative of) the vector describing the force of gravity (which is normal to the ground plane.) The Y-axis is parallel to the vertical edges of walls and windows, for example, commonly found in human construction. The Z-axis is parallel to the principal axis of the camera. Thus, the vanishing point $\mathbf{v_y}$ is the vertical vanishing point, and the vanishing points $\mathbf{v_x}$ and $\mathbf{v_z}$ are horizontal vanishing points.

4. The effect of camera position

The effect of various common camera positions on vanishing point locations can be examined by modeling the camera position with the **R** matrix. Of course, this matrix actually describes a rotation of the world coordinate frame (rather than the camera), but a rotation of the camera is equivalent to an inverse rotation of the world.

Figure 2: An image of a church facade captured with the world and camera coordinate frames, as described by Section 4.1. The vanishing point of the vertical lines is at infinity on the image *y*-axis. The vanishing point of one set of horizontal lines is at infinity on the image *x*-axis and the vanishing point of the other set of horizontal lines is at the principal point.

Technically, the **R** matrix is any matrix in the special orthogonal group *SO*(3). In practice, the camera positions used by consumer photographers follow a fairly predictable nonuniform distribution. For example, it is relatively rare for a photographer to capture an image with the camera pointed either straight up or straight down. Several classes of **R** matrices emerge, and these classes can be evaluated to determine which are related to the problem of images having a tilted appearance.

4.1. Default camera position

In this simplest case, the rotation matrix **R** is the identity. Each axis of the camera coordinate frame is parallel to its respective axis in the world coordinate frame as illustrated by Figure 1. Therefore, the vanishing point locations are:

$$\mathbf{V} = \mathbf{K} = \begin{bmatrix} \alpha & 0 & 0 \\ 0 & \alpha & 0 \\ 0 & 0 & 1 \end{bmatrix} \tag{5}$$

The vertical vanishing point $\mathbf{v_y}$ is located at infinity on the image *y*-axis. Horizontal vanishing point $\mathbf{v_x}$ is located at infinity on the image *x*-axis, while $\mathbf{v_z}$ is located at the principal point.

Figure 2 shows an image of a church building captured with a camera model with identity **R**.

4.2. World rotation about the Y-axis

In general, a photographer does not carefully align the principal axis of the camera so that it will be parallel to the horizontal lines of a building. In fact, such behavior would often result in uninteresting images. A more flexible model allows the photographer to walk around and shoot at the scene from an arbitrary position. This situation can be

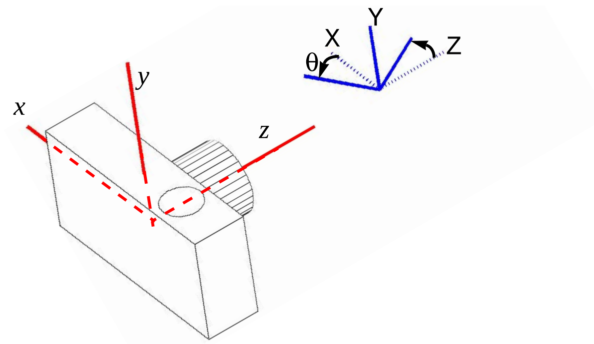

Figure 3: The geometry of the camera coordinate frame and the world coordinate frame where the world is rotated about the Y-axis by angle θ.

modeled as a world rotation by angle θ about the Y-axis, and is illustrated in Figure 3. For this category of **R**, the principal axis is parallel with the ground plane, but not necessarily parallel to either of the X- or Z-axes. In this case, the vanishing point matrix **V** is:

$$\mathbf{V} = \begin{bmatrix} \alpha\cos\theta & 0 & \alpha\sin\theta \\ 0 & \alpha & 0 \\ -\sin\theta & 0 & \cos\theta \end{bmatrix} \quad (6)$$

Again, the vertical vanishing point falls at infinity on the image *y*-axis because the vertical axis is still parallel with the image plane. Also, the horizontal vanishing points are confined to the image *x*-axis.

Figure 4 shows an image of the example church captured with a camera model exhibiting a rotation of the world about the Y-axis.

4.3. Tipping the world about the X-axis

Rotating the world by an angle ϕ about the X-axis is equivalent to tipping the camera up or down. This position is commonly used when photographing objects that are either above (e.g. the top of a tall building) or below (e.g. a puppy) the photographer. The principal axis of the camera is no longer necessarily parallel to the ground plane.

As a result, the vanishing point matrix is:

Figure 4: An image of a church facade captured with the world and camera coordinate frames as described by Section 4.2.

Figure 5: Tipping the scene about the X-axis. An image of a church facade captured with the world and camera coordinate frames as described by Section 4.3.

$$\mathbf{V} = \begin{bmatrix} \alpha & 0 & 0 \\ 0 & \alpha\cos\phi & -\alpha\sin\phi \\ 0 & \sin\phi & \cos\phi \end{bmatrix} \quad (7)$$

Each of the world coordinate axes' vanishing points are still located on an image axis.

Figure 5 shows an image of the church captured with a camera model having an **R** describing a rotation of the world about the X-axis. It is easily observed that the vertical vanishing point is no longer at infinity. However, as shown by (7), the vertical vanishing point is constrained to the image *y*-axis.

4.4. World rotation about the Z-axis

The camera can be rotated by angle -β about its principal axis. This is equivalent to rotating the world by angle β about the Z-axis, and often it results in an undesirable image composition.

In this case, the vanishing points are located at:

$$\mathbf{V} = \begin{bmatrix} \alpha\cos\beta & -\alpha\sin\beta & 0 \\ \alpha\sin\beta & \alpha\cos\beta & 0 \\ 0 & 0 & 1 \end{bmatrix} \quad (8)$$

The vanishing points $\mathbf{v_x}$ and $\mathbf{v_y}$ are rotated from the image *x*- and *y*-axes by the amount of the world rotation. Figure 6 shows an example image of the church with the

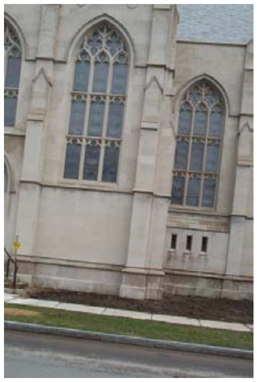

Figure 6: Rotating the scene about the Z-axis (by $\beta = 5.8°$). An image of a church facade captured with the world and camera coordinate frames as described by Section 4.4. The result is an image with poor composition.

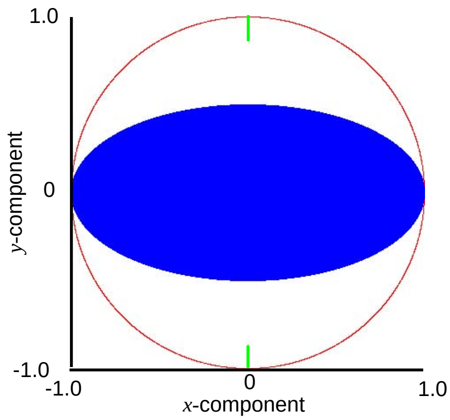

Figure 7: Range of vertical (green) and horizontal (blue) vanishing point locations for the camera model of Section 4.5 when $-\pi \le \phi \le \pi$ and $-\frac{\pi}{6} \le \theta \le \frac{\pi}{6}$.

camera rotated by $5.8°$ about the principal axis. The horizontal and vertical vanishing points are $5.8°$ from the image x and y-axes. In this image, the rotation clearly results in a distracting, unappealing appearance.

4.5. World rotation about X- and Y-axes

For this class of rotation matrix $\mathbf{R}$, the flexibility provided by the rotation matrices in Sections 4.2 and 4.3 is encompassed. This case best typifies general photography except with no rotation of the scene about the Z-axis. In other words, this model includes all "preferred" camera positions, ensuring that images contain no rotation as exhibited in Figure 6. In the most general sense, this scenario includes all camera positions for which the x-axis of the camera is kept parallel with the ground plane. It is equivalent to rotating the world about the Y-axis by angle θ, then rotating about the original X-axis by angle ϕ. The rotation matrix $\mathbf{R_{XY}}$ associated with this model is:

$$\mathbf{R_{XY}} = \begin{bmatrix} \cos\phi & 0 & \alpha\sin\phi \\ (\sin\theta)(\sin\phi) & \cos\theta & -(\cos\phi)(\sin\theta) \\ -(\cos\theta)(\sin\phi) & \sin\theta & (\cos\phi)(\cos\theta) \end{bmatrix} \quad (9)$$

The vanishing point matrix is calculated to be:

$$\mathbf{V} = \begin{bmatrix} \alpha\cos\phi & 0 & \alpha\sin\phi \\ \alpha(\sin\theta)(\sin\phi) & \alpha\cos\theta & -\alpha(\cos\phi)(\sin\theta) \\ -(\cos\theta)(\sin\phi) & \sin\theta & (\cos\phi)(\cos\theta) \end{bmatrix} \quad (10)$$

The important result for this case is that the vertical vanishing point $\mathbf{v_y}$ is still constrained to fall on the y-axis of the image. For images where the camera's x-axis is held parallel to the ground plane, the vertical vanishing point will be on the image y-axis.

In addition, the horizon $\mathbf{h_{xy}}$ is the vanishing line associated with the XZ-plane. The horizon has equation:

$$\mathbf{h_{xy}} = \mathbf{v_x} \times \mathbf{v_z} \quad (11)$$

In this case, the horizon can be shown to be parallel with the image x-axis.

It is interesting to observe the range of vanishing point positions that can occur for this camera model for reasonable ranges of ϕ and θ. When $\alpha = 1$, the vanishing point representation is identical to a homographic representation of the vanishing point. The vanishing point vector is normalized to magnitude 1, and the x- and y-components are plotted in Figure 7. The range over which vertical vanishing points (green) can be positioned is small compared to the possible locations of horizontal vanishing points (blue). Furthermore, the distributions of the horizontal and vertical vanishing points do not overlap.

Figure 8 shows an image of the church captured with a camera model exhibiting a rotation of the world about the Y-axis, then rotating about the original X-axis. As shown by (10), the vertical vanishing point is constrained to the image y-axis.

4.6. Additional rotation about Z-axis

Recall the vanishing points of the world coordinate axes as given in (3). Suppose that the world undergoes an additional rotation by an amount β about the original Z-axis. This rotation is equivalent to multiplying the original $\mathbf{R}$ matrix of the camera model by $\mathbf{R_Z}$, where

$$\mathbf{R_Z} = \begin{bmatrix} \cos\beta & -\sin\beta & 0 \\ \sin\beta & \cos\beta & 0 \\ 0 & 0 & 1 \end{bmatrix} \quad (12)$$

The new vanishing point locations, including the assumptions of square pixels, no skew, and assigning the principle point coordinate $[0\ 0\ 1]^T$, are

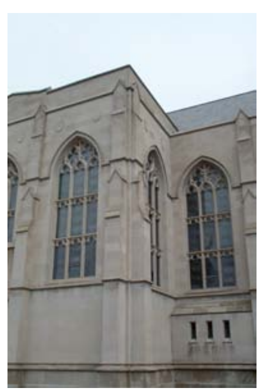

Figure 8: An image of a church facade captured with the world and camera coordinate frames as described in Section 4.5. The vertical vanishing point is forced to fall on the image y-axis. Also, the horizon is forced to be parallel with the image x-axis.

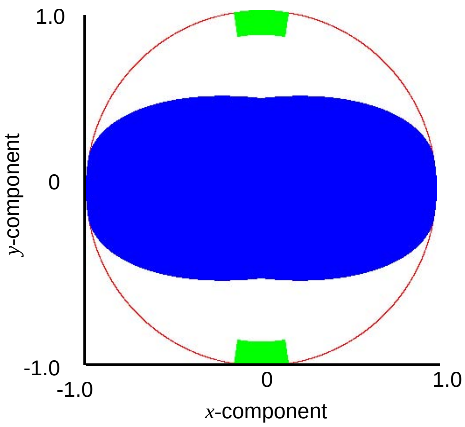

Figure 9: Range of vanishing point locations for the camera position of Section 4.6 when $-\frac{\pi}{20} \leq \beta \leq \frac{\pi}{20}$, $-\pi \leq \phi \leq \pi$ and $-\frac{\pi}{6} \leq \theta \leq \frac{\pi}{6}$.

$$\mathbf{V}' = \mathbf{K}[\mathbf{R_Z R}] = \mathbf{R_Z K R} = \mathbf{R_Z V} \tag{13}$$

Therefore, rotating the world about the principal axis has the same effect as rotating the vanishing points by the same angle about the principal point. This can be shown in general for any coordinate assignment of the principal point. This is a powerful result that can be exploited in an algorithm to automatically remove effects of accidental camera tilt from images.

Using the same plotting technique as in Figure 7, the range of possible positions of the vanishing points is shown in Figure 9 for magnitudes of β up to $9°$. The range of the vertical vanishing points (green) is still small and separated from the range of the horizontal vanishing points (blue). This leads us to suspect that location alone provides enough evidence to classify a vanishing point as a vertical vanishing point.

Figure 10 shows an image of the church captured with a camera model having an **R** representing a rotation about the X-axis followed by a rotation about the Z-axis.

Figure 10: An image of a church's facade captured with the world and camera coordinate frames as described by Section 4.6.

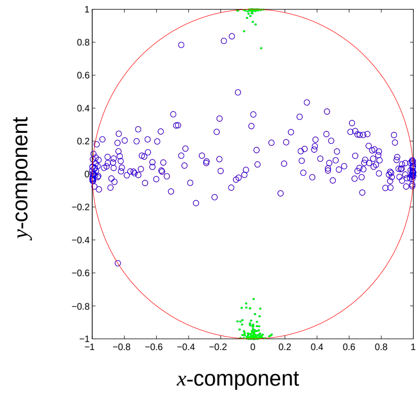

Figure 11: The distribution of manually identified vanishing points. Green dots represent vertical vanishing points and blue circles represent horizontal vanishing points. The vertical vanishing points are generally near the y-axis.

4.7. Camera position summary

To summarize, vanishing point positions of the common orthogonal set of directions found in human construction are a function of the camera's position. Under all normal camera positions (10), the vertical vanishing point is constrained to fall on the image *y*-axis. When the vertical vanishing point does not fall on the *y*-axis, the reason can be attributed to a rotation about the principle axis. Furthermore, the angle of rotation is equivalent, whether measured in the world or in the image (13). In addition, the horizontal vanishing points can be located in many different positions on the image coordinate system. Finally, vertical vanishing points have a small distribution, which is well separated from the distribution of horizontal vanishing points.

5. Ground truth data

A set of images was analyzed to determine whether the assumptions about typical camera positions have validity. Vanishing points from 352 typical consumer images were manually determined. From these images, 160 vertical vanishing points and 197 horizontal vanishing points were identified. The vanishing points were represented as unit vectors in 3-space by assuming a focal length *f* equal to the length of the diagonal of the image in pixels:

$$\mathbf{v} = \frac{\begin{bmatrix} v_x & v_y & f \end{bmatrix}^{\mathrm{T}}}{\left\| v_x \; v_y \; f \right\|} \tag{14}$$

Figure 11 shows a plot of the *x*- and *y*-coordinates of the manually identified vanishing point locations. As expected, the distribution of vertical vanishing points is small and clustered about the *y*-axis, while the distribution of the horizontal vanishing points is large. Because of the similarity between Figures 9 and 11, it appears that the camera positions examined in Section 4 adequately represent the typical camera positions of consumer photographers. Furthermore, the data confirms that in practice, the distributions of vertical and horizontal vanishing points have very little overlap, and classification of an unknown vanishing point can be accomplished with a high degree of confidence.

6. Automatic tilt correction

A camera unintentionally rotated about the principal axis (i.e., the Z-axis) results in an image with the undesirable appearance that the subject of the photograph is tilted or leaning. Fortunately, this situation can be improved by modifying the image in a manner that places the vanishing points at more desirable locations (i.e. the vertical vanishing point onto the image *y*-axis).

The goal of automatic tilt correction is to determine the amount of the rotation about the principle axis in the camera model from an analysis of the image's vanishing points. Then, the image is rotated to remove the effects of the Z-axis rotation. The result is a more aesthetically pleasing image that appears as if it had been captured with a camera having no rotation about the Z-axis. This result can be shown when the projection of the world onto the image is represented as:

$$\mathbf{x} = \mathbf{K}[\mathbf{R_Z R_{XY}}|\mathbf{T}]\mathbf{X} \tag{15}$$

by representing the rotation matrix $\mathbf{R}$ from (2) as $\mathbf{R_Z R_{XY}}$.

Then, rotating the image by the angle $-\beta$ can be written as:

$$\mathbf{R_{-Z}x} = \mathbf{R_{-Z}K}[\mathbf{R_Z R_{XY}}|\mathbf{T}]\mathbf{X} \tag{16}$$

where

$\mathbf{R_{-Z}}$ represents a rotation about the Z-axis by $-\beta$.

which, when $\mathbf{K}$ is assumed to be of the form in (4), can be shown as:

$$\mathbf{R_{-Z}x} = \mathbf{K}[\mathbf{R_{XY}}|\mathbf{T}]\mathbf{X} \tag{17}$$

This result is independent of the focal length.

By the result of Section 4.5, the rotated image $\mathbf{R_{-Z}x}$ has its vertical vanishing point on the image *y*-axis. In other words, rotating the image by the negative of the world rotation about the Z-axis results in the image of the world as if the camera model had no component of rotation about the Z-axis. For practical purposes, this excludes the effects related to the limited field of view of the camera.

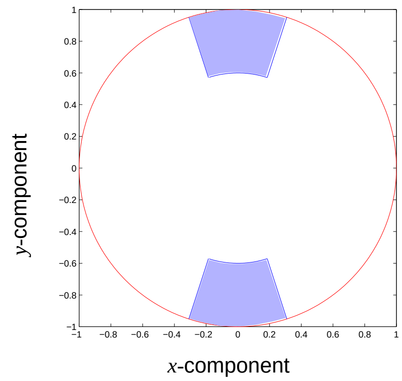

Figure 12: Vanishing points located inside the shaded region are classified as vertical vanishing points.

6.1. The algorithm

Images captured with a tilted camera can be corrected by finding the vanishing point of vertical scene lines, determining the angle of camera rotation based on the vanishing point, and rotating the image to produce a corrected image. With images from uncalibrated cameras, the assumption is made that the camera has no skew and has square pixels. To compute the angle of rotation, the principal point must be known or assumed (e.g. as the center of the image). It is assumed that the image is oriented correctly.

First, the image's vanishing points are identified. An automatic algorithm [1][4][5][8] can be used for this purpose.

Next, the detected vanishing points are examined to determine if any are candidate vertical vanishing points. Each vanishing point is represented as a unit vector, with (14). A pre-defined region, shown in Figure 12 and based on the ground truth data, is used for classification. Vanishing points falling within the shaded region are classified as vertical vanishing points, and other vanishing points are considered to be horizontal vanishing points. Considering only the ground truth data, this classification correctly classifies all vertical vanishing points (100%) and misclassifies only two horizontal vanishing points (99.0% correct) for an overall performance of 99.4% correct.

Next, if exactly one vertical vanishing point has been detected for the image, the estimated angle of rotation $\hat{\beta}$ is determined. The angle $\hat{\beta}$ is the angle between the *y*-axis and the line connecting that vanishing point and the principal point of the image.

The magnitude of the correction angle β_c is determined using $\hat{\beta}$, and an empirically derived relationship that is shown in Figure 13. This relationship was created based on the following observations:

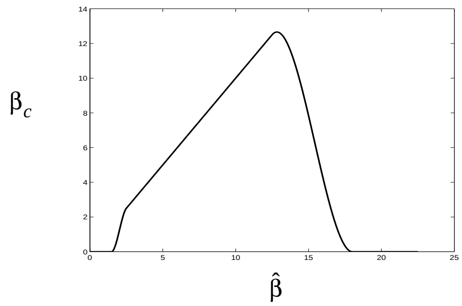

Figure 13: The relationship (in degrees) between the estimated camera rotation angle magnitude and the correction angle magnitude.

a) the effects of smaller rotations (e.g., $\hat{\beta} < 1.5°$) are difficult to observe in images. The image quality degradation associated with sharpness losses incurred by rotating the image probably outweigh any benefits of applying a rotational correction, and

b) very large camera rotations (e.g., $\hat{\beta} > 15°$) are often the result of intentional camera tilt, and therefore should not be modified.

Finally, the image is rotated by $-\beta_c$ to produce a corrected image. The rotational correction also incorporates the proper amount of zoom to avoid the appearance of void areas in the corners of the corrected image. The corrected image has its vertical vanishing point positioned on the image *y*-axis.

As alluded to in Section 4.5, an alternative method for estimating the camera tilt angle is to determine two horizontal vanishing points corresponding to orthogonal directions in the scene. The line connecting these points is the horizon. The angle between the horizon line and the image *x*-axis is the estimate of the angle $\hat{\beta}$. In practice, this method is difficult to automate because it requires the accurate detection of both horizontal vanishing points.

7. Results

Example original images and the corresponding corrected images are shown in Figure 14. The vertical vanishing point was correctly found on each image. In each case, the corrected image appears to be a large improvement over the original image.

One limitation of the algorithm is that the effect of camera rotation in images of non-structured scenes cannot be removed because a vertical vanishing point cannot be detected. Recall that in the Section 5, a vertical vanishing point exists for only 45% of the images. However, this is not as severe a limitation as it first seems. Empirically, the image content affects the perceived quality loss associated with the camera rotation. Typically, images of structured scenes suffer greater quality losses than images of non-structured scenes at the same levels of camera rotation. These structured scenes images are more likely to contain a detectable vertical vanishing point. Thus, the algorithm has its best reliability on images that are most important to fix.

8. Discussion and conclusions

In this paper, the relationship between commonly occurring camera models and the location of vanishing points in the image has been explored. It has been shown that, when the camera is in a desirable position relative to the world, the vanishing point of vertical scene lines is located on the image *y*-axis. However, undesirable camera positions can occur as a result of photographer error where the camera is rotated about the principal axis. The result of this condition is a vertical vanishing point rotated from the image *y*-axis and an unattractive image that appears to be tilted.

When this occurs, the image can be improved using the novel algorithm presented here. The vertical vanishing point of the image is found with an automatic algorithm, and the angle of rotation is determined. The image is rotated by the negative of this angle. This places the image vanishing point on the *y*-axis and results in a more pleasing composition of the image. The algorithm assumes that the principle point is in the center of the image, but requires no knowledge of the focal length.

Results of the algorithm are shown for a set of images. The algorithm performs well and produces pleasing images from original images that were undesirably tilted.

9. References

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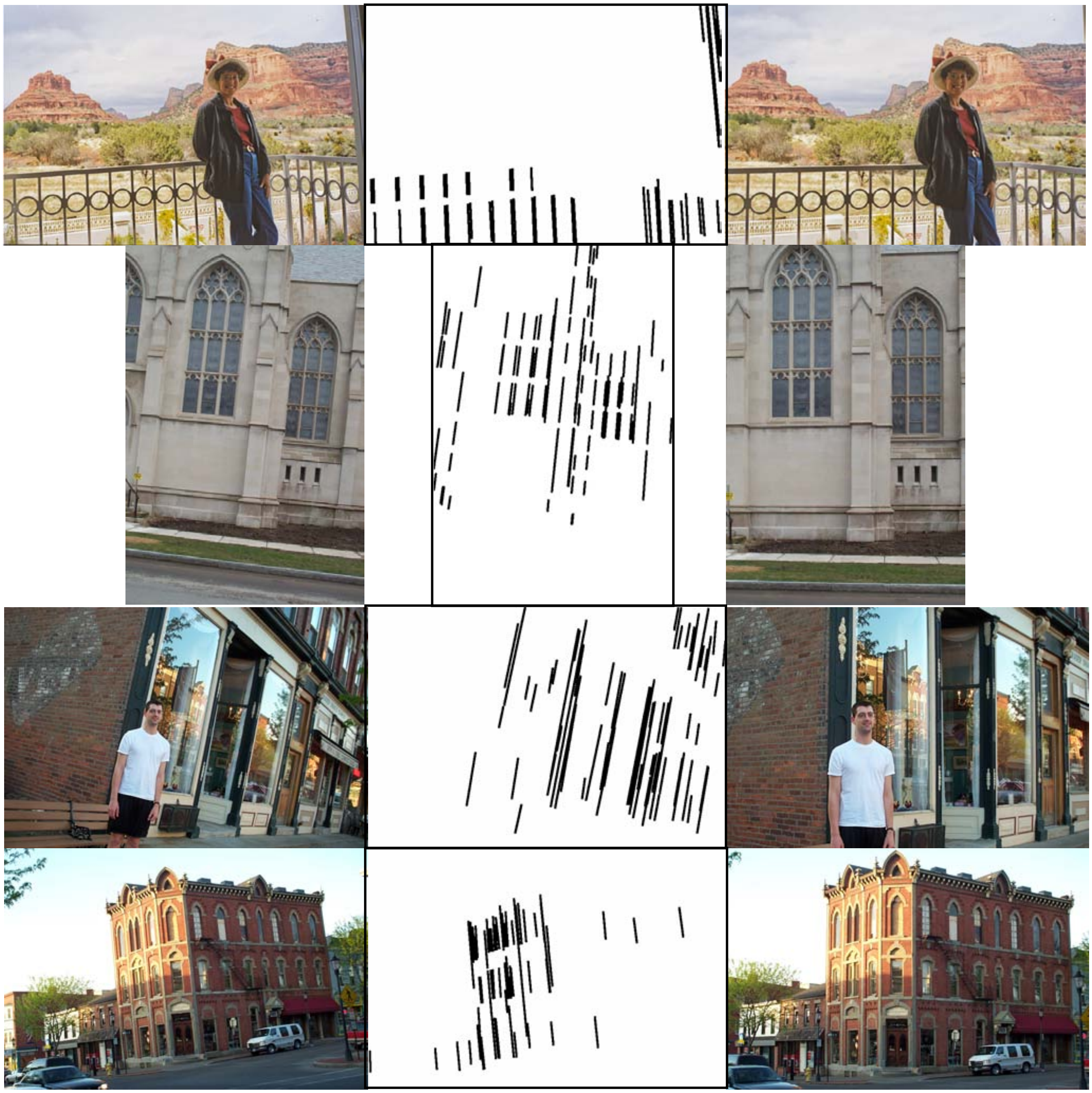

Figure 14: Examples of automatic tilt correction. **Left column:** Original Images. **Middle Column:** Detected lines associated with an automatically detected vertical vanishing point. **Right Column:** The resulting images after tilt correction. The corrections were -2.8 degrees, 5.8 degrees, 11.3 degrees, and -5.7 degrees from top row to bottom.