# Detection of Vanishing Points Using Hough Transform for Single View 3D Reconstruction

Fuan Tsai[1*] and Huan Chang[2]
[1] Center for Space and Remote Sensing Research, National Central University,
No.300, Jhongda Rd., Jhongli City, Taoyuan County 32001, Taiwan,
ftsai@csrsr.ncu.edu.tw
[2]Department of Civil Engineering, National Central University,
No.300, Jhongda Rd., Jhongli City, Taoyuan County 32001, Taiwan,
1984chang@gmail.com

*Corresponding author: ftsai@csrsr.ncu.edu.tw

## ABSTRACT

Single View Reconstruction (SVR) is a technique to reconstruct three-dimensional scenes or objects of interest from a single image. Unlike traditional (multi-view) close-range photogrammetry, SVR does not require camera parameters for obtaining 3D coordinates of the targets. A common approach for SVR is to establish the 3D metrology based on vanishing points from a single image with perspective projection. Therefore it is important to identify vanishing points correctly and effectively in order to obtain accurate 3D reconstruction results in SVR approaches. This study developed a double Hough transformation algorithm to estimate vanishing points on images with perspective projection. The algorithm starts by extracting feature lines of the raw image. The extracted feature edges are then transformed into Hough space, in which line segments are identified and short or discontinuous segments are discarded. The threshold for the line segment extortion and filtering can be automatically fine-tuned based on the statistical analysis of the data. For the best results, this study uses an inverted pyramid pattern iterative calculation procedure is employed to improve the line detection and filtering. Based on the peak values of the first Hough transformation, second transformation for those peaks is performed to identify line segments passing through the same point (or small area) on the image space. Finally, vanishing points are calculated according to the grouped line segments and optimized with iterative calculation. Experimental results using computer-simulated data and real images indicate that the developed algorithm can identify vanishing points effectively and the detected vanishing points can be used to reconstruct accurate 3D models of the objects of interest from a single image.

**Keywords**: image processing, vanishing point, close range photogrammetry, Hough transform

## INTRODUCTION

A vanishing point is referred to as the point in the perspective image space where a group of parallel lines in the object space converge. Vanishing points provide meaningful information in the real scene, such as viewers' orientation, depth information, object dimensions and so on. In a man-made environment, many regular structures and parallel lines are usually ubiqutious and they are useful for detecting vanishing points along three mutually orthogonal directions. Applications of vanishing points have been demonstrated in different fileds, including removing perspective distortion, providing geometric information, robotic navigation, camera calibration, 3D reconstruction and mosaic panoramic images etc. (Hartley and Zisserman, 2003; Chang and Tsai, 2009; Li et al., 2010; Brazin et al, 2012). As a result, detection of vanishing points is an important task in photogrammetry and computer vision applications.

Most vanishing point detection methods rely on line segments extracted from the image. Both in-door and out-door of man-made environments have plenty feature lines in the scenes parallel or orthogonal to each other, e.g. doors, windows, road marks, beam boundaries. In order to detect vanishing points automatically, line segments need to be clustered together into groups sharing the same intersection points. A popular approach is using a Gaussian sphere, which is centered on the optical center of the camera as an accumulator space (Barnard, 1983; Magee and Aggarwal, 1984;

Quan and Mohr, 1989). The advantage of this method is limiting all vanishing points into a finite space, but there are disadvantages because of the necessary quantization of the sphere. Hough transform based method is another similar approach to cluster line segments and detect the vanishing points (Tuytelaars et al, 1997; Dahyot, 2009; Li et al, 2012). Each cell in the Hough space lines the corresponding image point which pass through. Candidate vanishing points can be obtained by seeking maximal among these cells. However, the sensitivity of the quantization scales of the angular and radial bins might result in multiple detections (Shufelt, 1999).

Typically, the noise in an image might bring outliers and uncertainty into vanishing point detection and later reconstruction based on the detected vanishing points. Random sample consensus (RANSAC) is a simple and powerful method to distinguish and estimate the inliers or outliers under an unknown model (Fischler and Bolles, 1981). In a vanishing point detection task, RANSAC starts by randomly selecting two lines to intersect a vanishing point hypothesis, and then counts the number and cluster the lines passing through this hypothesized vanishing point. Repeat the process after several iterations, the vanishing point which maximizes the consensus set can be determined (Rother, 2002; Aguilera et al, 2005; Wildenauer and Vincze, 2007; Sinha et al, 2008). The problem of RANSAC is that the number of iterations may affect the restules. In addition, the systematic errors referring to the geometry information will increase because the vainishing points are dectected independently. A few algorithms were proposed to overcome the weakness of RANSAC, such as Multi-RANSAC (Zuliani, 2005), J-Linkage (Toldo and Fusiello, 2008; Tardif, 2009). The expectation–maximization (EM) algorithm is another popular method for finding maximum likelihood or maximize a posteriori (MAP) estimates of parameters in statistical models (Antone, 2000; Tardif, 2009). Other researches like using Thales' circle method (TCM) and Triangle area minimization (TAM) (Brauer-Burchardt and Voss, 2000; Kalantari et al, 2009), Helmoltz principle and minimum description length (MDL) criterion (Almansa, 2003), quasi-exhaustive search (Brazin et al, 2012) were also proposed to improve the detection of vanising points.

## METHODOLOGY

A double Hough transformation procedure is proposed to detect vanishing points in perspective projected images as illustrated in Fig. 1. The observation and meaning of detected features in each level of Hough transform are summarized in Table 1. The first Hough transform is commonly used to detect line segments in the image, where it is usual to only keep the dominant peaks in the normal-distance and normal-angle (ρ-θ) space. A second transformation for the peaks detected in the first Hough transform is employed to identify line segments passing through the same point (or small area) in the image space. Vanishing points are then calculated according to the grouped line segments and optimized with iterations. If necessary, a third Hough transform can be applied to the peaks of the second one to detect collinear vanishing points. An important case of this kind of feature is given by vanishing lines (e.g. the horizon line).

**Table 1. The meaning of the features detected under each Hough transform (modified from Tuytelaars et al, 1997).**

| Layer | Meaning of detected features |
|---|---|
| Layer 0 | Detected edge image |
| ↓ 1st Hough transform | points ~ lines<br>points ~ collinear points |
| Layer 1 | Line segments |
| ↓ 2nd Hough transform | lines ~ points<br>lines ~ collinear intersection points |
| Layer 2 | Vanishing points |
| ↓ 3rd Hough transform | points ~ lines<br>points ~ lines of intersection points |
| Layer 3 | Vanishing lines |

### *Feature lines detection*

The first step is to extract feature edges using Canny operators. Image enhancement might be helpful for improving edge detection, and image morphology could also be used for merging discontinuous lines before and after the edge detection. The parameterization of the Hough transformation is based on the orthogonal distance ρ of the line to the origin and the direction θ of the normal to the line. By transferring extracted feature edges to the ρ-θ space, straight feature lines can be detected automatically. For the best results, this study uses the inverted pyramid pattern iterative calculation for ρ-θ parameters, and the iteration stops when vanishing points are stable. A voting scheme is used to select candidate peaks from the accumulated histogram for collinearity detection in ρ-θ space. Afterward, similarity rectification is applied to identify different line segments. Least squares methods are then employed to trace line groups iteratively by adjusting the threshold of histogram peaks, until the number of line groups is satisfied. Figure 2(a) is an example image, on which each four points (blue and red) are collinear and each three lines intersect one point (black). Figure 2(b) illustrated the result after first Hough transformation, candidate peaks are marked (red and blue) and formed in line (yellow).

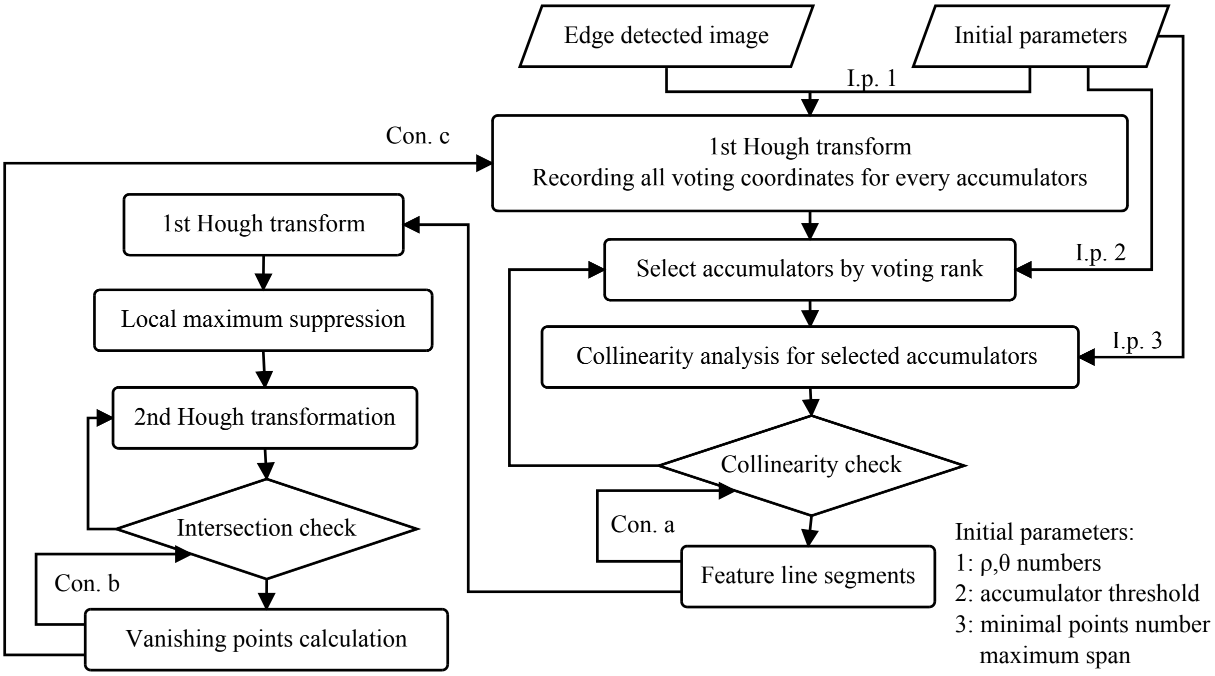


**Figure 1. The general procedure of the proposed vanishing point detection method.**

### *Vanishing points localization*

The second Hough transform (Layer 2) could be used directly after the first Hough transformation in the ρ-θ space (Layer 1), but some short lines or false positives will significantly decrease the accuracy of vanishing point calculation. That makes feature lines detection and filtering become indispensable. Based on the first Hough transform (Layer 1), the second transformation (Layer 2) clusters the line segments of the peaks in Layer 1 where several straight lines in the original image (Layer 0) intersect. Figure 2(c) shows the importance of local maximum suppression, which can limit the number of voting elements in the second Hough transformation. Finally, vanishing points are calculated according to the grouped line segments and optimized with iterative calculation. The procedure of vanishing point localization illustrated in Figure 1 contains three conditions for obtaining stable vanishing points are considered (Con. a, b and c in Figure 1). Condition 'a' is the number of line segments in each direction; i.e., adjusting line group number threshold to prevent most detected lines from pointing to a certain direction; Condition 'b' is the number of intersection points; Condition 'c' is that the representative vanishing points should be stable under different ρ-θ parameters. Modifying ρ-θ parameters can increase the reliability for vanishing point calculation. Figure 2(d) illustrates the result after the second Hough transformation and candidate peaks of intersect lines in the image space are marked (blue and red).

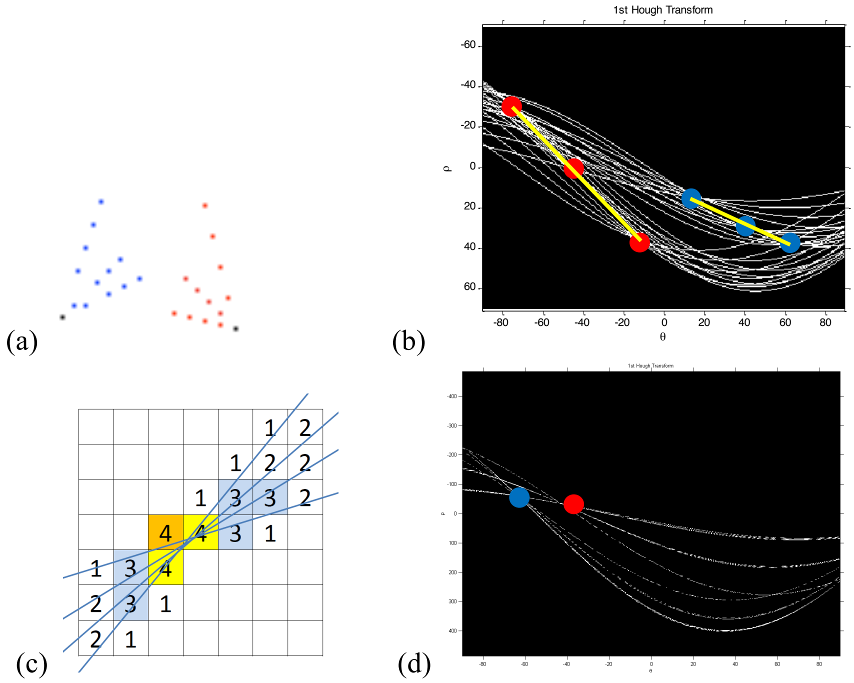


**Figure 2. An example of double Hough transform (a) raw image; (b) 1st Hough transform; (c) local maximum suppression; (d) 2nd Hough transform.**

### *Accuracy validation*

A vanishing point is an imaginary point in the image space on the basis of the perspective projection, therefore it cannot be measured directly. The accuracy of the detected vanishing points in this research is validated indirectly. The first validation is based on the collinearity condition equations, image principle points ($x_o$, $y_o$), rotation angles (ω, φ, κ) and focal length (f), which can be derived from Eq. (1) ~ Eq. (3). The comparison between calculated values and reference data quantitatively demonstrates the accuracy of the vanishing points. The second validation depends on the applications. Figure 3 shows an example how to estimate the line through detected vanishing points. In this figure, vanishing line ($L_v$) is the line passing thought the vanishing points $V_x$ and $V_y$, and it forms a reference plane with the origin. Feature point $F_r$ is at a known (or reference) distance $H_r$ to $B_r$ from the reference plane. Another feature point F is with an unknown distance H above the reference plane. Points B and Br are the base points for vertical distances on the reference plane. The four points I, F, B, $V_z$ are collinear. Point I can be obtained from Eq. (4), which projects point $F_r$ on to the line linked by F and $V_z$. Once a reference height, $H_r$, is defined, every feature points' height, H, can be calculated from Eq. (5). Estimated the length of known line segments can both visually and quantitatively validate the proposed method.

$$x_{Vx} = f\frac{-\cos\varphi\cos\kappa}{\sin\varphi} + x_O; \quad y_{Vx} = f\frac{\cos\varphi\sin\kappa}{\sin\varphi} + y_O \tag{1}$$

$$x_{Vy} = f\frac{\cos\omega\sin\kappa + \sin\omega\sin\varphi\cos\kappa}{\sin\omega\cos\varphi} + x_O; \quad y_{Vy} = f\frac{\cos\omega\cos\kappa - \sin\omega\sin\varphi\sin\kappa}{\sin\omega\cos\varphi} + y_O \tag{2}$$

$$x_{Vz} = f\frac{-\sin\omega\sin\kappa + \cos\omega\sin\varphi\cos\kappa}{\cos\omega\cos\varphi} + x_O; \quad y_{Vz} = f\frac{-\sin\omega\cos\kappa - \cos\omega\sin\varphi\sin\kappa}{\cos\omega\cos\varphi} + y_O \tag{3}$$

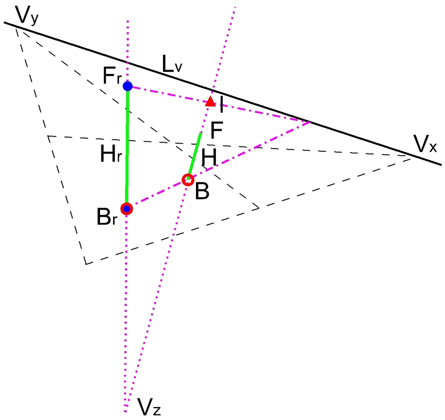


**Figure 3. Vanishing point geometry.**

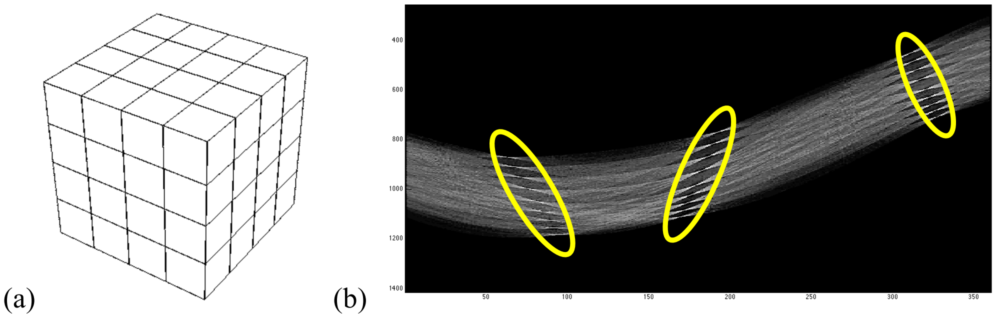
$$I = \overline{V_Z F} \times \overline{F_r \times L_V \times (\overline{B_r B})} \qquad (4)$$

$$H = \frac{\left\| \overline{FB} \right\|}{\left\| \overline{IB} \right\|} * H_r \qquad (5)$$

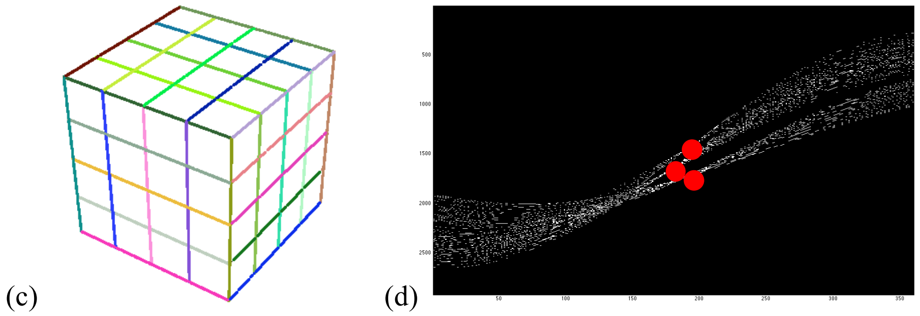
## EXPERIMENTAL RESULTS

A computer-simulated model is used to test the performance of the developed algorithms. The test case was generated using Google sketch-up and projected in perspective onto an image plane. In this example, errors from lens distortion, occlusions, structure geometry and projection can be neglect and complete reference data can also be used for quantitative evaluation. Figure 4 (a) shows the edge image of the computer-simulated model, and the transformed edge image in the ρ-θ space (Figure 4 (b)) with detected peaks (yellow circles). Figure 4 (c) shows the line segments derived from the 1st Hough transform, and each peak of the cell lines represents the corresponding image point (same color) which pass through. The 2nd Hough transformation of the local maximum of each cell in the 1st Hough space is illustrated in Figure 4 (d), where three highest peaks are marked in red dots. Figure 5 shows the three vanishing points and vanishing lines of a cube, where vanishing point is defined by a set of lines in the image projected by a set of parallel lines in the scene.

There are nine vertical line segments with the same length of the test image as displayed in Figure 6. Assuming segment e is the reference height, $H_r$, all other line segments can be calculated according to Eq. (5) and the results are listed in Table 2. The root mean square error (RMSE) is 0.674% and the maximum error is 0.87%, indicating that the vanishing points calculated using the proposed method is highly reliable. The other validation based on the collinearity condition equations is shown in Table 3. Reference data of computer-simulated model include three rotating angles, the mean error is 1.2° and maximum error is 2.0° .



(a) (b)



(c) (d)

**Figure 4. A computer-simulated model (a) Edge image; (b) 1st Hough transform highlight with cell peaks; (c) Detected line segments from (b); (d) 2nd Hough transform marked with cell peaks.**

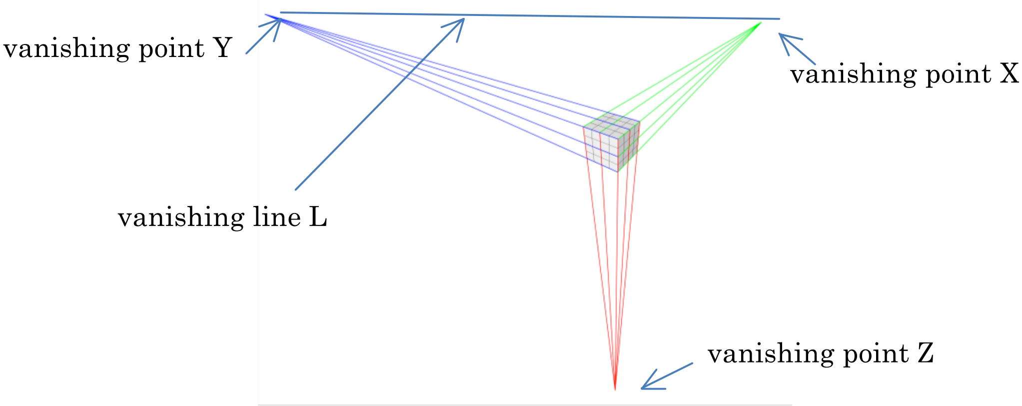


**Figure 5. The three vanishing points and vanishing lines of the test image.**

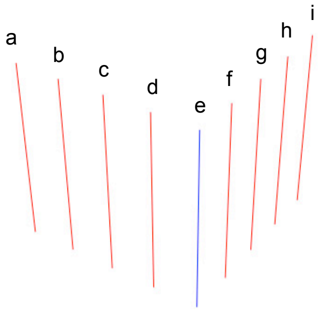


**Figure 6. Vertical line segments of the test image.**

**Table 2. The length of each vertical line segment estimated using vanishing points.**

| Fea. | Cal. | Ref. | Error Per. |
|---|---|---|---|
| a | 0.9926 | 1 | -0.74% |
| b | 0.9920 | 1 | -0.80% |
| c | 0.9976 | 1 | -0.24% |
| d | 0.9917 | 1 | -0.83% |
| e | --- | 1 | --- |
| f | 1.0066 | 1 | 0.66% |
| g | 1.0037 | 1 | 0.37% |
| h | 1.0061 | 1 | 0.61% |
| i | 1.0087 | 1 | 0.87% |

**Table 3. Orientation parameters derived from estimated vanishing points.**

| Orientation parameters | Calculation results | Reference data |
|---|---|---|
| $x_o$ | 11.15 (mm) | --- |
| $y_o$ | 10.66(mm) | --- |
| $\omega$ | 55.4° | 54.8° |
| $\varphi$ | 24.7° | 22.7° |
| $\kappa$ | 21.2° | 22.1° |
| f | 21.26(mm) | --- |

## CONCLUSIONS AND FUTURE WORKS

This study developed algorithms requiring only a single image with perspective view to detect vanishing points without internal or external camera parameters. The proposed method utilizes multiple transform operations to extract feature line segments and to detect vanishing points. Line segments and vanishing points can be extracted automatically with defined thresholds on the basis of Hough Transformation. Experimental results demonstrated that reliable accuracy in the vanishing points applications can be achieved with the proposed methods. Future improvement of the developed system will focus on the threshold fine-tuning problem and testing more complicate images.

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