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Extended Hough methodology in geo-spatial image exploitation

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ABSTRACT

Hough transform theory provides a heuristically appealing approach toward finding lineal features in imagery. Unfortunately direct algorithmic implementation of its theory results in many practical problems. We provide two interlocking theoretical extensions to greatly enhances the Hough transform's ability to handle finite lineal features and allow directed search for parallel lines within the scene while balancing memory and computational complexity. Both extensions involve expansion of the Hough space concept to allow easier access to processed data for both dedicated silicon and general-purpose computer implementations.

Keywords: Hough transforms, lineal features, image exploitation, algorithmic implementation

1. INTRODUCTION

Geospatial image exploitation can be key to the more efficient gathering of widespread and geographically dispersed data of wide use to governmental and industrial bodies. Such gathering of geospatial information can itself be partitioned into the gathering of natural and cultural features. Of these, cultural features are of the main interest in detecting man-made changes. Such changes, while quite varied in exact composition, usually result in one or more forms of observable lineal feature evidence being present in the collected imagery. Such lineal features range from the faint traces of ancient or abandoned roadways and hedgerows to the sharp well-defined edges of building structures and pavements. Thus what is needed is an automated feature detector which can robustly pick out lineal features.

2. THEORY

2.1 The Hough transform in theory

The Hough Transform was initially proposed to detect curves in bubble chamber photographs by Paul Hough in 1962, and later was patented by IBM.[1] It is a universal technique for detecting geometric primitives, such as straight lines, circles, ellipses, etc, by converting the problem to a rather simple local peak detector in an alternate Hough space.[2] We are here concerned with the lineal version.

Consider object points in image space (the *xy*-plane) as shown in Figure 1 Each such object point, say object point A, in image space has an infinite number of straight lines that could pass through it according to its slope-intercept representation, $y_i = \alpha x_i + \beta$. Rewriting this representation as $\beta = -\alpha x_i + y_i$ and upon realizing that α and β can take many possible values; one can construct an $\alpha\beta$-space, which is also called the Hough space. In this new Hough space, the equation for all possible lines going through point $A(x_i, x_j)$ is represented as $\beta = -\alpha\ x_i + y_j$. Thus, a single point in an image space corresponds to a straight line in the Hough space as shown in Figure 1(b).

Two object points in image space form two lines in the Hough space. Their intersecting point, *C* of Figure 2, in the Hough space corresponds to that line passing through their points in the image space (object points *A* and *B* in our example*)*. If *n* straight lines in the Hough space intersect at a point in Hough space, then the intersection of these *n* Hough space lines reside on the same single straight line in image space. Thus the problem of determining the location of lines in image space is replaced by determining the locations of points in Hough space where many lines crossover.

Not only is the technique simple and intuitive, it also possesses robustness to image artifacts since missing or occluded object pixels simply reduce the number of lines crossing over at points in Hough space. Thus once a Hough space is developed, the line detection problem in an image space becomes a considerably simpler local maxima searching problem in Hough space.

2.2 The Hough transform in practice

The crucial flaw in the slope-intercept Hough approach above relates to the parameters α and β. Since their ranges are infinite ($-\infty < \alpha,\ \beta < \infty$), not all of their values can be represented in practice. The problem becomes most acute when $\alpha \to \infty$, i.e. for a vertical line. With a line slope of infinity, the *y*-intercept of a line becomes negative infinity. Since the Hough space is normally represented by use of a finite memory array, this leads to being unable to detect vertical lines.

One way to partially overcome this problem is by using an alternate analytic representation of lines.[4] A straight line can be expressed in polar coordinates as $\rho = x\cos\theta + y\sin\theta$ where the pair (ρ, θ) defines a vector from the origin to the nearest point on the line. Thus, this vector will be perpendicular to the line as shown in Figure 2.

Now consider a point (*x*, *y*) in image space. There are again an infinite number of lines that pass through this point, and each of these lines has an associated vector (ρ, θ). These vectors plot out the equation $\rho = x\cos\theta + y\sin\theta$ in $\rho\theta$-space. Thus, a straight line in the Hough space above forms a sinusoidal curve in $\rho\theta$-space. Figure 3 shows five sinusoidal curves in $\rho\theta$-Hough space that correspond to five points on a line in image space. As before, the intersection of these (however now curved) lines in Hough space gives α, β parameters for the original line in image space.

The main utility of the $\rho\theta$-Hough space is that it can easily handle vertical lines arising in image space. But this occurs at the severe price of increased computational complexity and masking of certain other useful properties discussed in Section 3.3 below.

3. Extensions to Hough theory

3.1 The dual space Hough transform

To overcome both of the deficiencies of the above Hough Transforms, consider forming two separate linear Hough spaces. The first Hough space contains the information of those image space lines that lie between –45 and 45 degrees from the *x*-axis ($-1 < a \leq 1$). The second space includes the information of those image space lines that lie between 45 and 135 degrees ($-1 < a' \leq 1$). See Figure 4.

Construction of the first space is trivially the original basic Hough transform over the slope range between -1 and 1. The second Hough space can easily be achieved by using the *x*-intercept and inverse of the line's slope instead of the *y*-intercept and slope respectively. This altered transform can be considered as simply rotating the *x* and *y* axes by 90 degrees counterclockwise and again applying the original basic Hough transform over the new resultant slope range between -1 and 1. The resulting dual Hough space can now collectively handle image lines of all slopes including vertical. Further, each sub-space retains the quite useful linear nature of the original Hough transform discussed above. Also by eliminating computationally expensive trigonometric operations in the second approach above, all transforms can now be accomplished by simple additions by using the concept of coherence as frequently used in Computer Graphics.[5]

3.2 3-D Hough transform

The dictionary definition of a 'line' is "a geometric figure formed by a point moving along a fixed direction. "[6] Also in mathematics, a line implicitly implies infinite length. However, a line segment, i.e. a line with a specific length, is much more meaningful in feature extraction where all lines have beginnings and ends, e.g. sides of buildings, agricultural fields, road markings, etc.

A line segment needs two additional parameters over that of a pure line in order to be precisely represented: the starting and ending positions. Since the standard forms of lineal Hough Transform utilize only slope and *y*-intercept information, they consider that every line candidate of an image has infinite length. This Hough transform inability to detect a specific line segment greatly inhibits its use in real-world feature extraction. For example, extracting a building in an image requires producing a set of line segments with various lengths and end points. In order to accomplish this task, the Hough space as normally applied requires the use of a four-dimensional array. However, we show here a means of adding just one more dimension to the dual 2-D Hough space presented above to accomplish the same results.

By augmenting the above dual space Hough transform with a third parameter, the *x*-axis of image space, the Hough space becomes two three-dimensional arrays, Figure 5. Notice that all lineal feature evidence in this extended Hough space is parallel within a plane. This is caused by the fact that information within a single plane is from the same column of the input image. For each image pixel on the same column, the increment/decrement rate of intercept is consistent as slope increases or decreases. Since the set of planes contains information from each image column sequentially, a line segment with a specific starting and ending points can be detected by utilizing only necessary planes. The most distinctive advantage of this extended Hough methodology is thus an ability to detect any desired length line segment from an image. Another advantage is increased adaptability to a high-level vision system's hypothesis feedback mechanism. This is further enhanced by the fact that constructing the three-dimensional Hough space is a one-time process. This three-dimensional space can then be projected and re-projected on the fly onto dual two- dimensional Hough spaces on the fly as required.

3.3 Directed search for related features

The extended combination of the dual and 3-D Hough space concepts introduced here obviously allows for improved search for individual line segments. However, due to the simple regular nature of the resulting extended Hough space, it now becomes increasingly possible to search for related higher-level features, including corners, parallel lines - both orthographically and in perspective.

Parallel line detection is a significant strength of our extended Hough methodology. Since all parallel lines in an input image have the same slope, their corresponding points will be located vertically in our extended Hough space as shown in Figure 6. Figure 7 shows the same effect taken with an actual Hough space of a real image. This ability is especially important because many man-made objects contain parallel line segments. Relevant high-level examples include buildings viewed in overhead imagery, rectilinear objects in orthographic projections, etc. Similarly, corners, Figure 8, can be found on horizontal lines in the extended Hough space, separated by 90 degrees. The corner point will itself be found at some specific x position along the third axis.

Edges of three-dimensional objects in perspective imagery can be detected using the following vanishing point based search. Depending on the perspective viewpoint there are one, two, or three vanishing points for most objects including hexahedrons. When a perspective based image has a vanishing point at (x_v, y_v), all edges that pass through the vanishing point are formed on a line $b = -x_v a + y_v$ in the dual Hough space. Figure 9 depicts this phenomenon. With the vanishing point established, the Hough space can be yet further regularized such that all image lines passing through the object's vanishing point are aligned on a horizontal line $b = 0$ of the Hough space. This can be realized by moving the image's origin to the vanishing point (i.e. moving the image reference axes to $y = x_v$ and $x = y_v$) as shown in Figure 10. This of course allows easier searching for other parallel lines in perspective image space.

4. CONCLUSION

The extensions to classical Hough theory presented here have been shown to provide new insights into how to continue to adapt the Hough methodology for practical applications.

Use of the dual space Hough transform technique avoids the complex space-warping techniques required by other extensions to bound the basic Hough Transform memory requirements and the need to decode the resultantly complex results in a now-warped Hough space. Our particularly simple piecewise linear dual space Hough transform technique both nicely bounds the memory requirements while allowing for easy interpretability. We have shown how this easy interpretability can be used by higher-level processes to search for other related features including parallel lines and corners. To our knowledge, we have also shown for the first time an ability to find such feature in perspective side look as well as orthographic down look imagery.

The 3-D Hough transform extensions developed here also address another critical deficiency of the more classical Hough transform implementations: that of handling finite length linear features. Our technique reduces computational complexity by use of available memory to permit simplified search for the endpoints of each lineal feature. An additional advantage of this extension is that faint short lines missed by more classical techniques can now be more easily detected.

Both of the extensions reported above have been designed to allow the very regular forms of transform calculations and bounded memory requirements needed for direct implementation in dedicated silicon as well as on general-purpose computer platforms. These details will be reported later, but can lead to drastically speadup of processing and the potential for direct incorporation into overhead sensor platforms.

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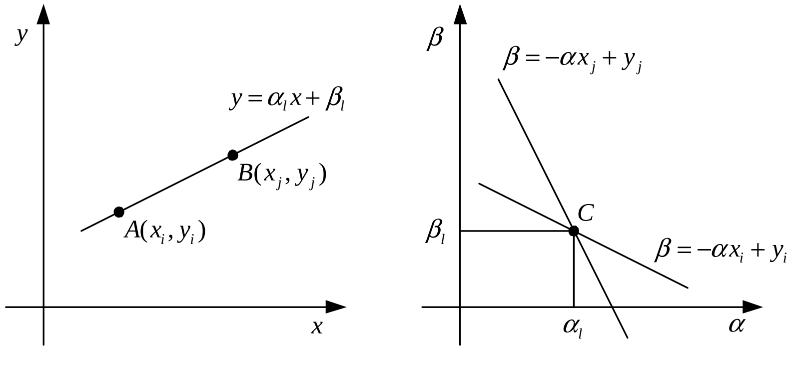


(a) Image space (b) Hough space

Figure 1. Slope-Intercept Representation of the Hough Transform

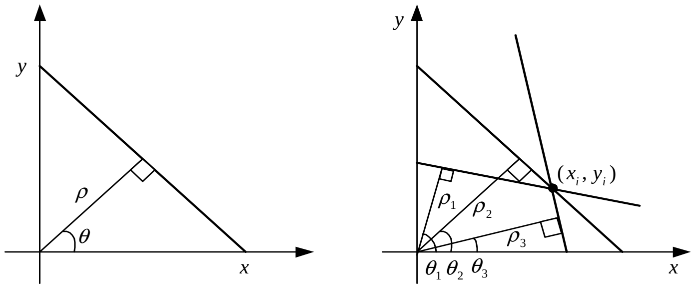


Figure 2. Polar Representation of the Hough Transform

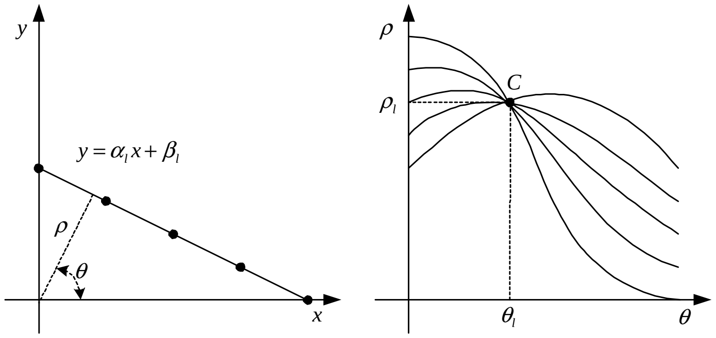
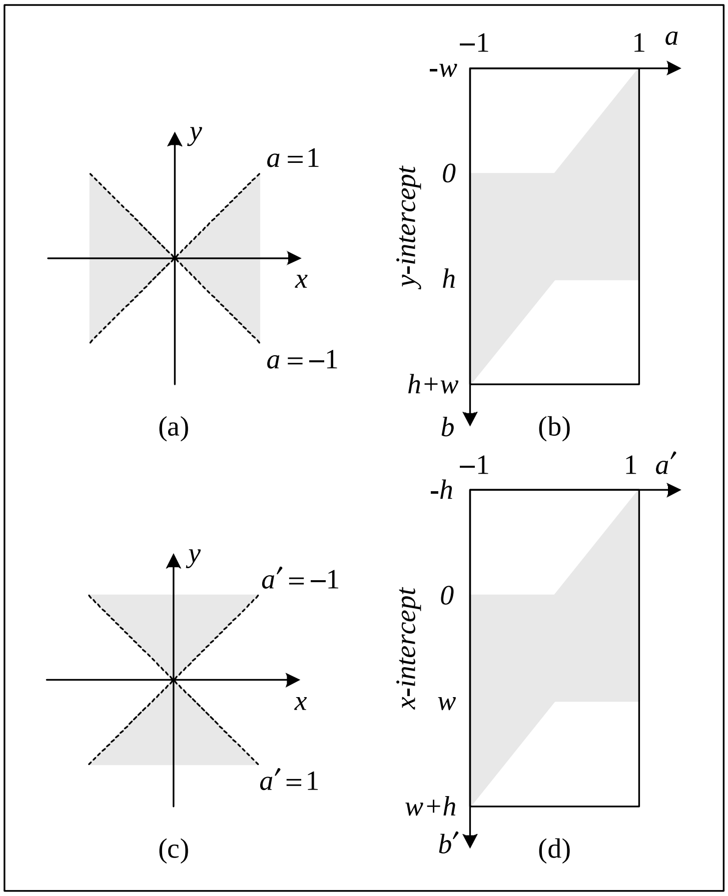
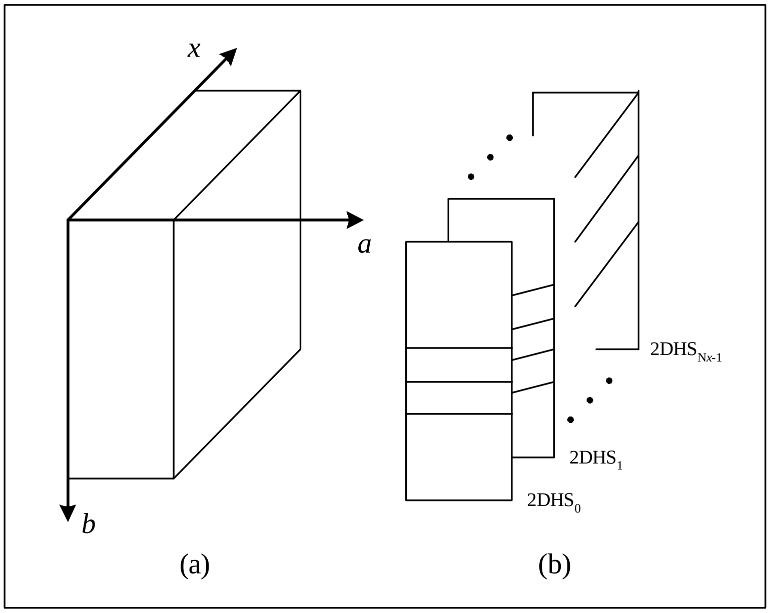


Figure 3. Image Pixels and Corresponding Sinusoidal Curves in $\rho\theta$-Space



(a) Image Area Covered by First Space (b) First Hough Space
(c) Image Area Covered By Second Hough Space (d) Second Hough Space

Figure 4. The Dual Hough Space



(a) Three-dimensional Hough Space (b) As an Array of Two-dimensional Hough Spaces (2DHS)
Figure 5. Three-dimensional Hough Space Concept

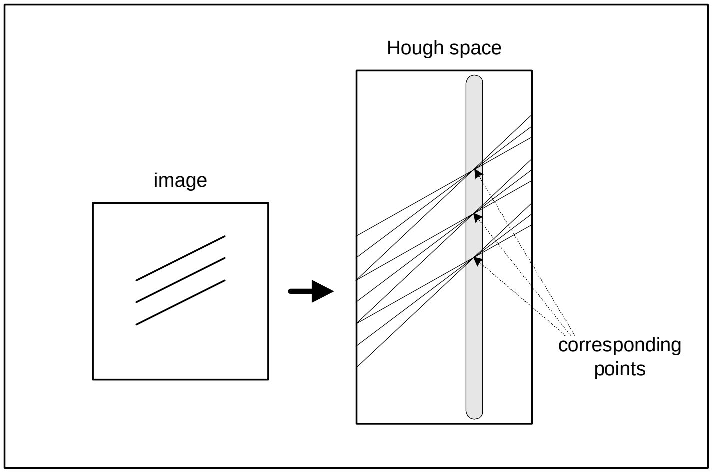
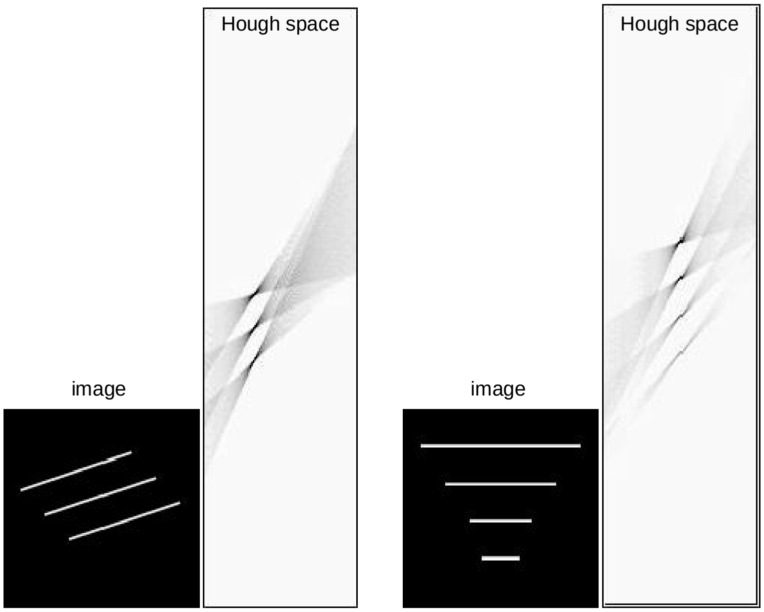


Figure 6. Parallel Lines in Image Space result in Points along a Vertical Line in Hough Space



(a) (b)

Figure 7. Actual Hough Space Representation of Parallel Lines

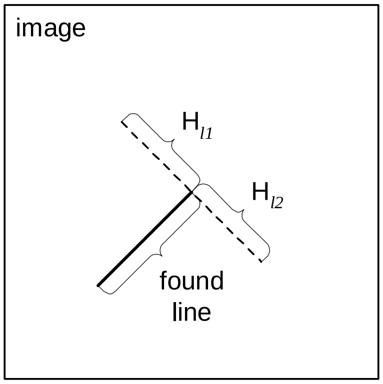


Figure 8. Two Line Segments forming a Corner

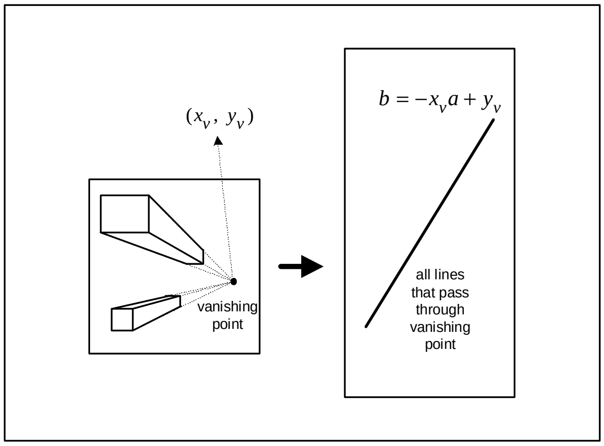


Figure 9. Vanishing Point in a 3D Perspective View

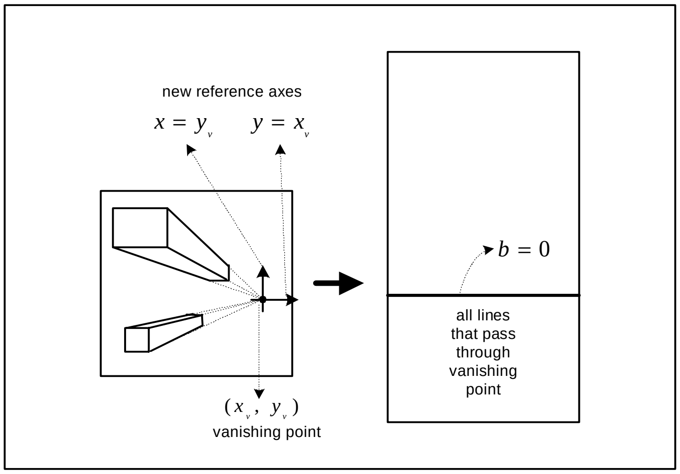


Figure 10. Vanishing Point Effect Using New Reference Axes