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ABSTRACT

In an effort to make automatically detect image features for pattern recognition, we described a 3-dimesional (3-D) Hough transform. We describe two interlocking theoretical extensions to greatly enhance the Hough transform's ability to handle finite lineal features and allow directed search for various features while balancing memory and computational complexity. We computed the 2-D Hough transform of 1-D slices of an image which results in a 2-D to 3-D transform. Features such as line segments will cluster in a particular location so that both line orientation and spatial extent can be determined. This approach allows the Hough transform to be more widely applied in pattern recognition including 3-D features.

Keywords: automated feature extraction, Hough transform, image exploitation, pattern recognition

1. INTRODUCTION

The Hough transform (HT) has seen useful but limited application in the field of pattern recognition.[1-3] As a line to point mapping the HT has been primarily used for detecting lines and parametric curves. An important property of the HT is that segmentation results are robust to imperfect data or noise.

Although the HT has been demonstrated to be useful for detecting lines, it is not widely used for other purposes. The main reason in the case of lineal features is that the true length of a line segment is generally difficult to determine by the HT. Line segments or other lineal features such as roads, and edges of objects, are especially important in many pattern recognition applications. Using post-processing may improve the flexibility of the HT. One method has been developed to find line segments, but it is computationally intensive.[4] In addition, the use of a hybrid shape recognition system that uses an incoherent optical HT and a neural network for classification algorithms has been demonstrated.[5] A modification of the HT to detect line or curve segments is needed. Such a transform could form the basis of a particularly fruitful approach to feature detection.

We computed the 3-D HT of an image in an effort to make features more readily apparent. We computed the 2-D HT of 1-D slices of an image. This results in a 2-D to 3-D transform, but allows features to be easily detected. Features such as line segments will cluster in a particular location so that both line orientation and spatial extent can be determined. This approach allows the HT to be more widely applied in pattern recognition.. In the next sections, we briefly review the HT, describe our 3-D approach, and describe some examples of our approach.

2. CONVENTIONAL HOUGH TRANSFORM

The HT 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. The HT is a global operation that maps a line to a point. Consider object points in image space (the *xy*-plane) as shown in Fig. 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 Fig. 1(b).

One of the most popular uses of the HT is to identify lines in noisy images Two object points in image space form two lines in the Hough space. Their intersecting point, *C* of Fig, 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. Therefore the Hough space is usually searched for local maxima where the parameters of lines that connect the points in the input image are determined 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.

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 $\alpha \rightarrow \infty$, 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.[6] 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. 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 below.

Another disadvantage of the HT when used to detect lines is that the extent of the line is difficult to determine. When valid points in the HT are found, only the equation of the line in known. Further processing must be used to determine the extent of a line. Because of the computational complexity, and the limited use of the HT, it has not been widely used.

3. EXTENDED HOUGH TRANSFORM

3.1 The dual space Hough transform

We overcame both of the main deficiencies of the HT by first considering two separate linear Hough spaces. The first Hough space contains the information of thr 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 the image space lines that lie between 45 and 135 degrees ($-1 < a' \leq 1$) as shown in Fig. 2.

Construction of the first space is the original basic HT 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 HT 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 HT 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. [7]

3.2 3-D Hough transform

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 form of the HT uses only slope and *y*-intercept information, it considers that every line candidate of an image has infinite length. This 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. We show here a means of adding just one more dimension to the dual 2-D Hough space presented above can determine the length of line segments.

By augmenting the above dual space HT with a third parameter, the *x*-axis of image space, the Hough space becomes two three-dimensional arrays as shown in Fig. 3**.** We will assume here that the *x*–axis corresponds to the direction of the rows of an image, but our discussion holds for either the row or column direction. We plotted each point in the 2-D Hough space as a point in the 3-D Hough space at (α,β,x). This is equivalent to sliding a vertical slit across the image and plotting the 2-D HT for each position and assembling the transforms into a 3-D space. 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.

Note that every point in the 3-D Hough space relates to exactly one point in the input image. Thus, the 3-D Hough space is a remapping of 2-D image coordinates to 3-D space. For example, the 3-D HT of a point will be the 2-D HT of the point at the value of *x* that the point exists in the input. The remainder of the volume will be zero. In general, features will cluster in a particular way so that both feature detection and position may be more easily determined than in the 2-D HT.

3.3 Pattern recognition

The 2-D to 3-D transform, may allow some features to be more easily detected when compared to using the 2-D transform. In the 3-D HT, the image coordinates have been reorganized into a form allowing for more advantageous searching for image boundary features. The extended combination of the dual and 3-D Hough space concepts introduced here obviously allows for improved search for individual line segments. When considering the HT of a line segment, it is difficult to determine the extent of the line. In the 3-D HT, contributions from a line segment will only exist in planes at particular values of *x*. In terms of feature extraction, we can effectively look for a line segment between specific *x* coordinates. 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.

Slightly curved segments can pose a problem for the HT. Curved segments can be found with the 3-D HT in a similar way to that of straight lines. The change in position of the HT from one plane to the next along the *x*-axis indicates the direction of the curve.

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 4. Figure 5 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 6, 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 7 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 8. This of course allows easier searching for other parallel lines in perspective image space.

4. CONCLUSION

We described a 3-D HT of an image by computing the 2-D HT of 1-D slices of an image that results in a 2-D to 3-D transform. Features such as line segments will cluster in a particular location so that both line orientation and spatial extent can be determined. This approach allows the HT to be more widely applied in pattern recognition. Conceptually, the 3-D space can be searched for evidence of desired or opportunistic features. 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. The 3-D Hough space approach is probably a good way to conceptualize the search processes needed, and more clustering algorithms need to be developed based on this approach.

The 3-D HT extensions developed here address the main deficiency of the conventional HT implementations: that of handling finite length lineal 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.

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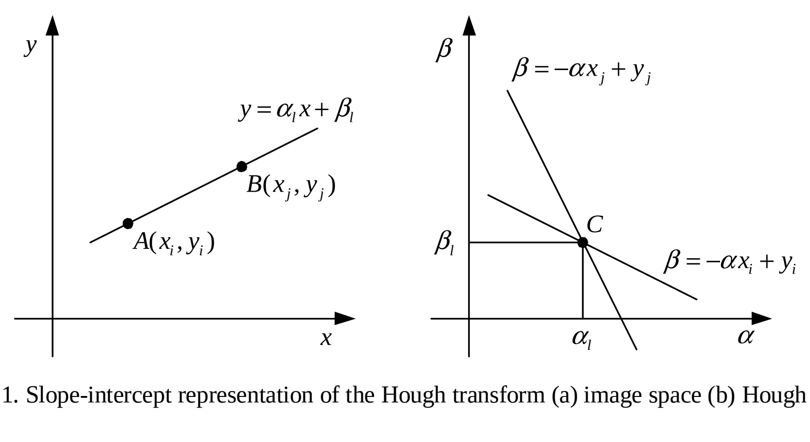

Figure 1. Slope-intercept representation of the Hough transform (a) image space (b) Hough space

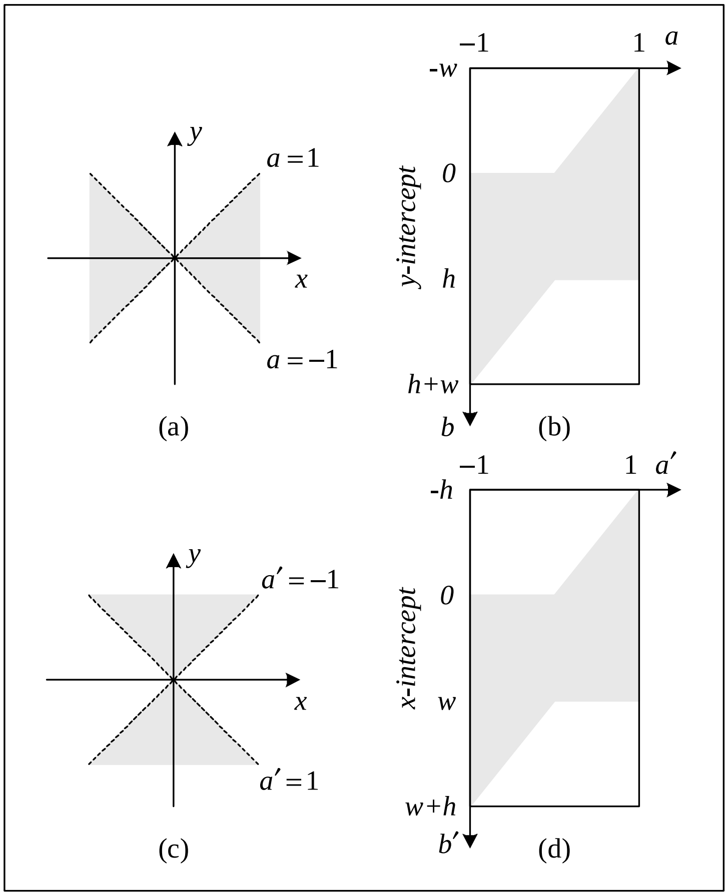

Figure 2 The dual Hough space (a) image area covered by first space (b) first Hough space (c) image area covered by second Hough space (d) second Hough space.

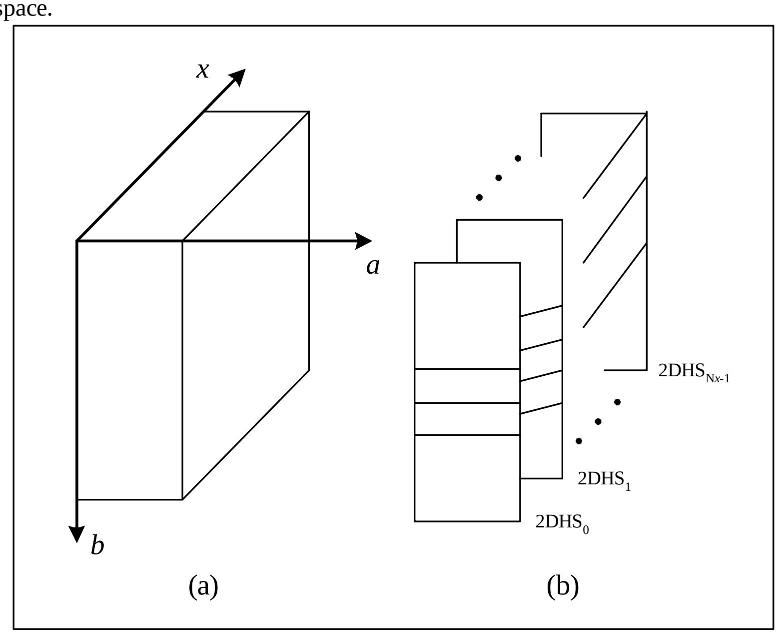

Figure 3 Three-dimensional Hough space concept (a) three-dimensional Hough space (b) as an array of two-dimensional Hough spaces.

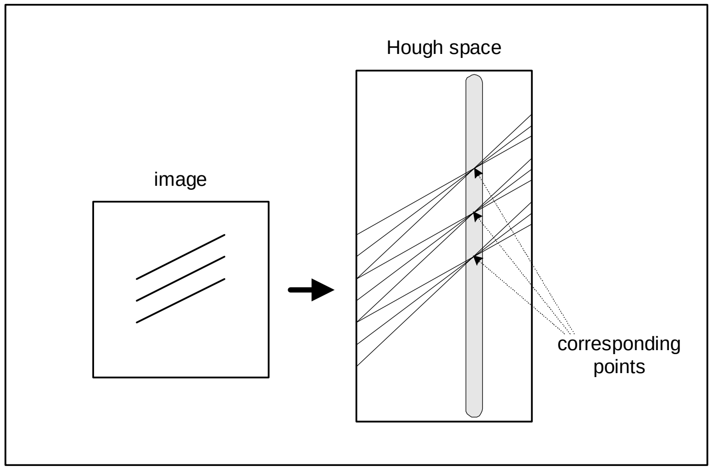

Figure 4 Parallel lines in image space result in points along a vertical line in Hough space.

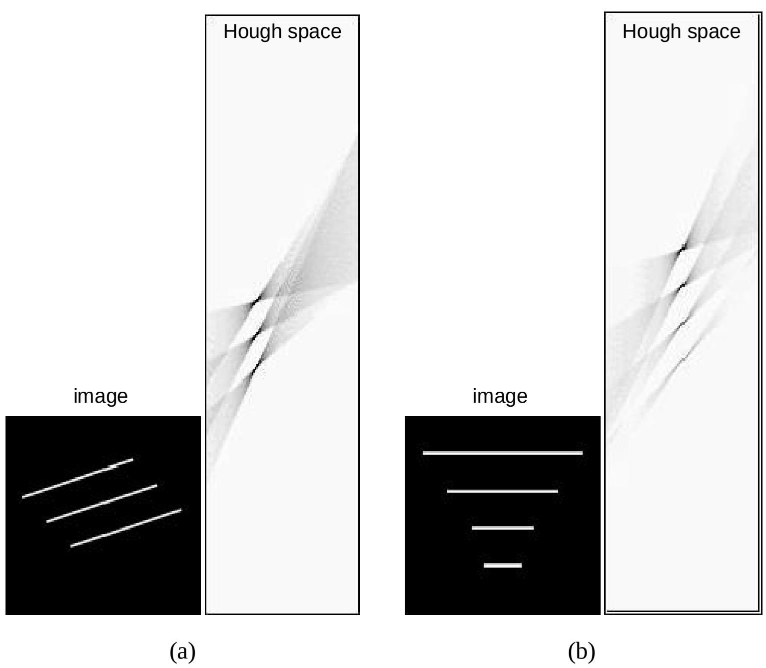

Figure 5 Actual Hough space representation of parallel lines.

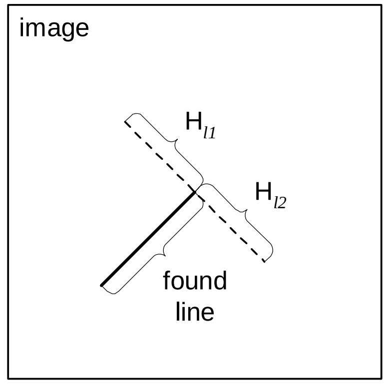

Figure 6 Two line segments forming a corner.

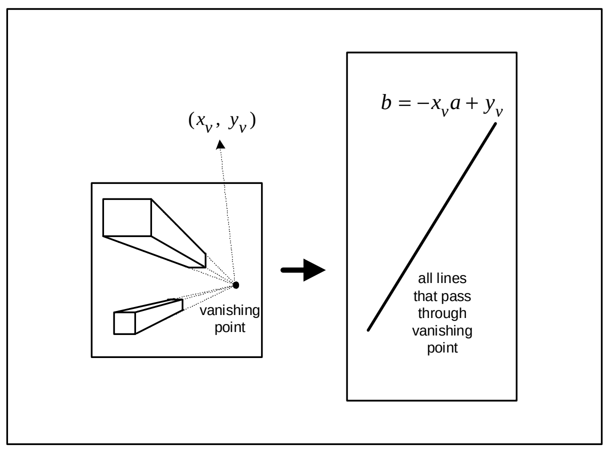

Figure 7 Vanishing point in a 3-D perspective view.

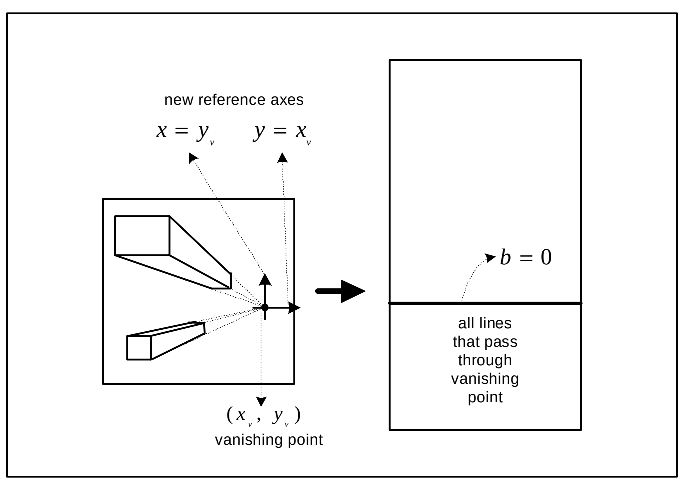

Figure 8 Vanishing point effect using new reference axes.