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Kou-Hu Tzou
Toshio Koga
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INTRODUCTION

Since its inception in 1986, the Visual Communications and Image Processing conference has grown steadily: this year the total number of submissions reached nearly 260. Members of the review committee spent several weeks coordinating a review process of the abstracts submitted and accepted 190, separating them into three parallel sessions. Due to the large number of accepted papers and the limited time slots, some papers that were scheduled as oral presentations were assigned to poster sessions.

The papers are divided into two volumes, according to subject. It is hoped that such division can make future reference more convenient. Volume 1605, Visual Communications, addresses video sequence coding, hierarchical image decomposition, vector quantization, model-based image coding, superhigh-definition image systems, still image coding, image transmission and communication systems, motion estimation and motion analysis, 3-D motion analysis, hierarchical image coding, entropy coding, and visual communication hardware. Volume 1606, Image Processing, contains papers on image analysis, morphology and fractals, pattern recognition, motion perception and moving target detection, image restoration and filtering, human visual system models, image segmentation and classification, digital image processing in medicine, image sequence restoration and filtering, digital image processing algorithms, VLSI implementation and hardware architectures, applications of digital image processing, and neural networks in image processing. Since there is no clear line between visual communication and image processing, we were confronted by the question of where to assign certain topics. In such situations, we tried to do the assignment by majority in that session.

Special thanks are due to the program committee and session organizers for their efforts in soliciting papers of topical interest and high quality. We would also like to extend our appreciation to the SPIE staff for taking care of all the details associated with the conference.

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SESSION 1B

Image Analysis I

Chair
Alan C. Bovik
University of Texas/Austin

Grouping and forming quantitative descriptions of image features by a novel parallel algorithm

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ABSTRACT

Grouping disconnected edgels and forming quantitative descriptions of structural entities are fundamental tasks in image understanding. Our newly developed grouping algorithm, the Distributed Hough Transform (DHT), is capable of performing both of these tasks. The DHT uses the principle of Proximity Weighted Symmetry (PWS). PWS is based upon non-accidentalness, viewpoint invariance, and new probabilistic models of projected angles and distances which use the assumption that boundaries of man-made objects can be represented by circular arcs and straight lines. Experimental results show that the DHT is a robust algorithm.

1. INTRODUCTION

The objective of our research is to group image edge elements (edgels) into structurally significant entities. Edgels are discrete elements of an intensity discontinuity and they are extracted from an image by first calculating and then thresholding and thinning the gradient of an image. Grouping is often performed on edgels since they tend to correspond to object boundaries in the real world. Edgels extracted from true images are usually disconnected and do not form continuous curves. Therefore, grouping based on continuity, even incorporating gap bridging,[1] is very difficult and in many instances does not yield favorable results.

We group edgels into features because it provides us with structural descriptions of the objects in an image. To perform grouping, we use a novel dispersed algorithm that we refer to as the Distributed Hough Transform.[2] Non-accidentalness and viewpoint invariance are combined to determine a Proximity Weighted Symmetry measure for relations between edgels.[2] The Proximity Weighted Symmetry measure is utilized by the Distributed Hough Transform not only for grouping purposes, but also to form explicit quantitative descriptions of the features in an image. Although the formation of quantitative descriptions is not a direct goal of grouping, it is essential for higher level image understanding tasks.

1.1 Proximity Weighted Symmetry and the Distributed Hough Transform

We have developed a principle that we call Proximity Weighted Symmetry (PWS) to aid in grouping edgels. The principle of PWS naturally unifies the laws of perceptual organization.[3] More importantly, it is based upon non-accidentalness, viewpoint invariance, and newly developed probabilistic models of projected angles and distances. This allows a probabilistic measure of the three-dimensional structural significance of an edgel to be determined. Symmetry has been used by many other researchers[4-11] but not in conjunction with exact probabilistic models[15] that have an important role in assessing the relative significance of symmetry relations. The principle of PWS is used by a novel dispersed aggregation method that we call the Distributed Hough Transform (DHT). The DHT uses PWS to detect curvilinear relations between edgels, and it accumulates support for the curvilinear features indicated by these relations. The support that an edgel accumulates for a feature reflects the probability that the edgel is a member of this feature. Since a probabilistic model of projected structures is incorporated, the DHT groups edgels into features that are likely to correspond to objects in the three-dimensional world. Other methods of detecting structural entities[12,13] are serial in nature whereas the DHT is inherently parallel. The DHT also provides explicit quantitative descriptions of the features in an image, and these descriptions can be used immediately for higher level image understanding tasks.

The DHT has significant advantages over the conventional Hough Transform. One advantage is that the DHT requires a parameter space of only one dimension for the detection of circular arcs, whereas the conventional Hough Transform requires a three-dimensional parameter space. The dimensionality reduction is achieved by distributing the transform among the edgels in the image. Thus, the global transform is cast into many local transforms, each of which is only one-dimensional. Another advantage of the DHT is its ability to consider local properties such as

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proximity. The conventional Hough Transform lacks the ability to consider local properties and it only accumulates global information.

The DHT is an inherently parallel process. This allows the transform to be implemented in a parallel processing machine in which the one-dimensional transforms for many edgels can be computed simultaneously. An artificial neural network can also be used to implement the DHT. An outline of such a network is presented in Section 8.

2. SYMMETRY

There are two significant relations that can be formed by two edgels in an image: symmetry and parallelism. We concentrate on the relation that we believe to be more significant for the description of curvilinear features: symmetry. Fig. 1 illustrates several configurations of symmetric edgels in which edgel A is symmetric to each of the other edgels. For each pair of symmetric edgels there exists a circle to which both of the edgels are tangent. As a consequence, the angles that each edgel forms with the displacement line joining the edgels are equal. Thus, each pair of edgels is symmetric with respect to the perpendicular bisector of the displacement line. Symmetry relations depend on both the relative displacement and orientation of participating edgels. This additional dependence on relative displacement gives symmetry more significance as a non-accidental relation than parallelism, which depends only upon orientation. We note that edgels A and E are not only symmetric, but they are collinear as well. This relation exemplifies the case of symmetry for which the edgels are both tangent to a circle of infinite radius. A straight line is simply a circular arc with zero curvature. If we can detect symmetry (and therefore circular arcs), we can also detect collinearity (and therefore straight lines). Since curvilinear features are usually smooth curves which have slow changes of curvature, they can be quite accurately approximated by a union of circular arcs and straight lines. These are the features that are detectable by the DHT.

2.1 Symmetry and Perceptual Organisation

The laws of perceptual organization[3] are based upon proximity, similarity, continuation, closure, symmetry, and familiarity. We claim that the principle of PWS encapsulates these laws. In the previous section we have described the relationship between symmetry and curvilinearity. This relation corresponds to the continuation law of perceptual organization. The law of closure follows naturally since edgels which are symmetric are part of a circle, and all circles are closed figures. The laws of similarity and familiarity pertain to complete shapes. These laws are not to be included in this initial stage of grouping for which the goal is not to group shapes but to group the elements composing each shape. The final law that has yet to be related to symmetry is proximity. This this law can easily be accounted for by including a proximity factor with a measure of symmetry. The result is a proximity weighted symmetry measure which concisely combines the laws of perceptual organization into one criterion.

2.2 The Symmetry Measure

Let us consider the relation between two edgels in an image. Fig. 2 shows two edgels, E_a and E_b. Edgel E_a is located at position (x, y) and forms an angle of ϕ with the horizontal. Edgel E_b is located at position (u, v) and forms an angle of ξ with the horizontal. Let us call the points where edgels E_a and E_b are located, A and B respectively. The displacement line, $\overline{AB}$, which joins the two edgels, forms an angle a with edgel E_a and an angle b with edgel E_b. To avoid ambiguity, both angles are measured from C, the center of the displacement line. Thus, angle a is measured in the counterclockwise direction, and angle b is measured in the clockwise direction.

The measure of symmetry for such a pair of edgels is a function of the relative location and orientation of the edgels and it is thus a function of $(x-u)$, $(y-v)$, ϕ, and ξ. However, the symmetry measure can be expressed more concisely as a function of the angles a and b. We can therefore write:

$$S[(x-u),\ (y-v),\ \phi,\ \xi] \equiv S(a,\ b) \tag{1}$$

where

$$S(a,\ b) = \frac{\left|\, |a-b| - \pi/2 \,\right|^{m}}{(\pi/2)^{m}} \tag{2}$$

The constant m is a control parameter and its effect on the symmetry measure will be illustrated shortly. Equation (2) assigns a value of unity to an exact symmetry relation. The measure, S, has meaning for other relations as well, since it actually reflects the degree of symmetry present in a relation. It is important for our measure of symmetry to indicate the amount of symmetry present rather than *decide* whether or not the edgels are symmetric because, as Marr stated with his principle of minimum commitment, it is unwise to make a decision until all relevant information has been accumulated.[14] We can always threshold our measure of symmetry at a later time, if we so desire. Equation (2) is also designed in such a way that large jumps in S are avoided for small deviations of angles a and b.

Let us consider an edgel with an orientation, $\phi = 0°$. This edgel forms a symmetry relation with a second edgel located at a relative displacement angle of 45°. Using various values of m, we plot the symmetry measure, S, as a function of the orientation, ξ, of the second edgel. These plots are illustrated in Fig. 3. Note that the symmetry measures are continuous and have high values at and near the orientation of exact symmetry. The control parameter m controls the width of the peak, and it therefore controls how close to an exact symmetry relation edgels must be in order to obtain a high measure of symmetry. For $m = 0$, the symmetry measure is equal to unity for all relations. As m increases, the peak narrows, and in the limiting case where $m = \infty$ only perfectly symmetric edgels will produce a non-zero symmetry measure. If the second edgel is located at a different relative displacement angle, the plots of S are simply shifted so that the peaks coincide with the angle of exact symmetry.

3. NON-ACCIDENTALNESS AND VIEWPOINT INVARIANCE

The goal is to construct groups of edgels in a two-dimensional image that correspond to structures in the three-dimensional world. So far, only a measure of symmetry has been developed, and this is insufficient in itself for grouping. The significance of symmetry relations must be determined, and the principle of non-accidentalness is ideal for this endevour. Obviously, more consideration should be given to relations that posses a higher probability of arising from non-accidental features in the image. Therefore, symmetry relations must be weighted by an importance measure that takes into account the non-accidentalness of these relations. Such a measure cannot be determined without a relevant probabilistic model. The novel probabilistic models of projected angles and distances that were recently published[15,16] allow for the derivation of explicit formulae that can be used to bestow proper weights to symmetry relations.

Since the content of scenes is generally not known *a priori*, the explicit probability that certain relations will be present in an image cannot be determined. However, the probability that a relation will occur by accident can be determined. Relations that have a low probability of occurring by accident are significant, and relations that have a high probability of occurring by accident are not significant. The viewing direction of an image is usually also unknown, and so viewpoint invariance must be considered as well. If a relation in the three-dimensional world is detectable when viewed from most orientations then it has a greater probability of being present in an image and is therefore more significant. Some such viewpoint invariant relations are collinearity, parallelism, curvilinearity, and proximity. These properties are more stable through changes in the viewing direction then are properties such as relative orientation or position.[15,16] Our grouping algorithm is based upon the viewpoint invariant relations of collinearity, curvilinearity, and proximity.

The significance of a relation can be determined by comparing the probability that the relation is conserved through viewpoint changes to the probability that the relation is accidental and does not have a high probability of accurately reflecting the true state of nature. In order to derive probabilities for determining significance, some assumptions must be made about the statistics of the image and the three-dimensional structures which produced the image. The Observability Sphere[15,16] can be used to compute the probability of observing certain relations such as curvilinearity or proximity.

The weight given to each symmetry relation should be proportional to the probability that the relation is a product of a true symmetry relation in the scene. Let us consider a pair of edgels in an image and define several events which describe possible relations between these edgels. Event t is the event in which the edgels are symmetric in the image and this symmetry relation is caused by symmetry in the scene. Event c is the event in which the edgels are symmetric in the image, but this symmetric relation is accidental, and there is no corresponding symmetry in the scene. Event s is the event for which the relation is symmetric in the image. Events t and c are mutually exclusive and cover the space of event s. Thus, the probability of having a symmetry relation in the image (event s) is given by:

$$P(s) = P(t) + P(c) \tag{3}$$

Using the fact that $P(s \mid t) = 1$, the conditional probability of event t given event s is:

$$P(t\,|\,s) \;=\; \frac{P(t)P(s\,|\,t)}{P(s)} \;=\; \frac{P(t)}{P(s)} \;=\; \frac{P(t)}{P(t)+P(c)} \tag{4}$$

Equation (4) can be used to calculate the probability that a symmetry relation in an image is the result of a symmetry relation in the scene, based solely on the prior probabilities $P(t)$ and $P(c)$. All that remains to be done is to derive expressions for $P(t)$ and $P(c)$.

To determine the probabilities $P(t)$ and $P(c)$, we assume that pairs of symmetric edgels in an image are created by the projections of circular arc segments in the three-dimensional scene onto the image plane. In this case, the angular displacement, D, between the edgels is a function of their separating distance d:

$$D(d) \;=\; \pi - 2\arcsin\left(\frac{d\rho}{2}\right) \tag{5}$$

where ρ is the curvature of the circular arc. For a given curvature, as the distance between the edgels is increased from zero, the angular displacement decreases from π. This simply means that as the distance between edgels on an arc increases, they become less and less collinear. The probabilistic models indicate that as the angular displacement approaches $\pi/2$, the probability that the projected angular displacement, D', will differ from the true angular displacement increases.[15,16] The probability that the projected angular displacement will be within the range $D\pm\delta$ depends on both δ and D. The probability of obtaining a certain projected angular displacement given an angular displacement in the scene is given by:

$$p(D'\,|\,D) \;\approx\; A\,\exp(-\,|\,D'-D\,|) \tag{6}$$

where A is a constant. The probability that the projected angular displacement will be within $D\pm\delta$ can thus be written as:

$$P(\,|\,D-D'\,|\leq\delta) \;\approx\; 2A\int_0^{\delta}\exp(-\alpha x)\;dx \tag{7}$$

Equations (6) and (7) were derived from the probabilistic models of Ben-Arie.[15] In order to determine the values of A and α, the normalizing condition:

$$P(\,|\,D-D'\,|\leq\infty) \;=\; 2A\int_0^{\infty}\exp(-\alpha x)\;dx \;=\; \frac{2A}{\alpha} \;=\; 1 \tag{8}$$

is used to determined that $\alpha = 2A$. Now the probability can be written as:

$$P(\,|\,D-D'\,|\leq\delta) \;=\; 1 - \exp(-2A\,\delta) \tag{9}$$

Using the probabilistic models again, the constant A is given by:

$$A \;\approx\; 10.95\;|1-2D/\pi|^{\;35} + 0.575\,\exp(1.275\;|1-2D/\pi|) \tag{10}$$

The explicit probability function $P(\,|\,D-D'\,|\leq\delta)$ in terms of d, δ, and ρ can be determined by substituting equations (5) and (10) into the right hand side of equation (9). For fixed δ and ρ, the probability that projected symmetry is caused by symmetry in the scene decreases considerably as the distance, d, between edgels increases. This is an expected result since as the distance between symmetric edgels increases, the angular displacement also increases, and as the angular displacement approaches $\pi/2$, the probability of preserving the symmetry relation through imaging transformations decreases.

The prior probability to detect a true symmetric relation within a distance, d, from an edgel is dependent upon three factors: (i) the probability, P_e, of general edge detection, which is assumed to be constant over the image; (ii) the distance, d, which is roughly proportional to the arc length; and (iii) the probability that the symmetry relation is viewpoint invariant, that is $P(\,|\,D-D'\,|\leq\delta)$ for some small δ. The probabilities P_e and $P(\,|\,D-D'\,|\leq\delta)$ are independent. Thus, the probability to detect a true symmetry relation is given by the proportion:

$$P(t) \;\propto\; d\;P_e\;P(\,|\,D-D'\,|\leq\delta) \tag{11}$$

Let us assume that the density of non-symmetric edgels in an image is constant and denote this density by ρ_1. The probability to detect an accidental symmetry relation is given by the proportion: