Phase-Based Edge and Bar Detection

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Abstract

Edges and bars are low level features which can be used as primitives for complex visual tasks. This paper considers the detection and localization of one dimensional edges and bar-like targets of a particular width. The algorithms use local phase information obtained by filtering the image with a Gabor kernel to identify edge and bar-like structures, utilize local frequency and amplitude information to reject measurements from particular regions where the Gabor output may be suspect, and to rank the measurements that are recovered. Applications of the algorithms to real images indicate the promise of this approach.

Keywords: Edge and bar detection, Gabor filter, Phase technique.

Introduction

Low-level vision forms the first stage of computation in a large number of vision systems. The success of high level computer vision processes depends upon good output from the low-level system. Although the gray level elements of the digitized image contain all of the information concerning image structure, the intensities are not directly related to the structures or features of the image, some low-level visual task must reorganize the raw image information into a representation based on meaningful scene features. Many vision systems utilize an "edge" as this low-level representation. In images, significant scene structures are often associated with sharp changes or discontinuities in the image intensity. These discontinuities are generally called edges. Consider the problem of detecting edges in the simpler case of a 1D image. Even in the limited 1D case, there are many possible types of edges. These edge types can be characterized by their local intensity profiles. Some examples of these are: (1) step, (2) roof, (3) ridge and (4) staircase which are shown in Figure 1. Bars correspond to ridge edges. Although extensive results have been reported by many researchers on edge detection, it is still worthy of exploration. One type of edge that has received less attention is the bar or ridge edge. Step edge may be a good primitive for some visual tasks, however, it is not the only available primitive. Other basic primitives are possible and may be better suited to particular tasks. Consider, for example, an application in which images consist of line drawings in which the width of the lines plays an important part in terms of understanding the image. Such a situation occurs when a visual system must be applied to maps or blueprints. In this type of application, a "bar" of a particular width might be a more suitable primitive representation of the image.

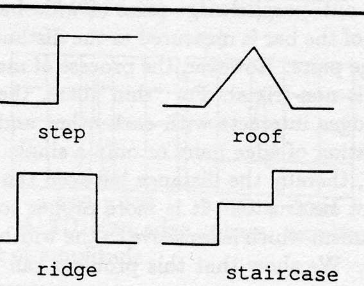

Figure 1: Edge Profiles

Many different techniques are available for identifying edges. The idea underlying most edge detection mechanism is differentiation, such as gradient operators (Roberts, Sobel, etc) and second derivative operators (Laplacian of Gaussian, etc). Noting the importance of phase in an image, we try to study edge behavior in terms of phase — reduce the problem of edge detection to the problem of finding appropriate features in the phase space.

A ridge edge or bar is a strip lying on a background with a relatively uniform grey level. Although bar masks[1] can be applied to reveal the presence of bars, we are interested in finding bars of particular width rather than any bar-like targets. A "wide" bar can be considered to be two step edges with opposite orientations, separated by some distance. Many edge finding techniques could be applied to the task of locating anti-parallel edge pairs of wide bars and the width of the bar is measured as the distance between its edge pairs. However, the process of matching the edges is non-trivial. For "thin" bars, the two adjacent edges interacts with each other and results in dislocation of edge pairs or only a single edge is detected, thereby the distance between the edge pairs can not be trusted. It is more proper to develop a mechanism which is sensitive to the width of bar-like target. We show that this problem can also be reduced to phase measurement.

We define models for the desired features, an edge and a bar. Following earlier phase based work[3,6, 4,7,2], we introduce the notion of the use of image phase as a localization measure which is independent of the features' intensity, and we derive properties of the features in phase space that can be easily identified in an image. Then we show how the local phase can be used to detect candidates of edge and bar of particular width in a scene, amplitude information and local frequency can be used to discard unreliable phase regions and undesired features. Finally, we present some examples which indicate the promise of the technique.

Phase-Based Edge and Bar Detection

Recent advances in stereopsis[3,4] and motion understanding [2] have approached the problem as one which utilizes the phase (or phase difference) of the underlying signal as the primitive upon which the more complex computation is to be handled. Jepson and Fleet[5] have shown how local frequency information can be used to identify regions in which the local phase information can be trusted. In the following sections we show how the problem of edge and bar detections can be reformulated as phase measurement processes. In 1D case, the process can be formalized as follows:

i) define a mathematical model of the desired feature
ii) choose proper filters
iii) filter the desired feature
iv) derive the phase property to identify the desired feature
v) phase may not uniquely characterize the desired feature or there are exist regions where phase information can not be trusted; to detect the desired feature, other information may be needed, such as local frequency, amplitude or derivative of amplitude.

In short, assuming:
i) I is the space of local image,
ii) F is the model of the feature we are looking for and $F \subset I$,
we try to derive property p which is a subset of $P(\phi(F), \phi'(F), \rho(F), \rho'(F))$ from the following maps:

$$\phi,\ \phi',\ \rho,\ \rho'$$

each of them of domain I and range real. In the next section, we give the definition of phase, amplitude and local frequency from Gabor filtering.

Phase, Amplitude And Local Frequency From Gabor Filtering

Gabor functions are complex functions which take the form of : $e^{i\omega_0(x-x_0)}e^{-\frac{(x-x_0)^2}{2\sigma_0^2}}$ Although other filters choices are possible, we choose Gabor functions as our bandpass filters, as they optimize the trade-off of joint uncertainty in space and spatial frequency by achieving the theoretical lower limit. Without loss of generality, take $x_0 = 0$ and consider the Gabor function defined as:

$$\mathrm{Gab}(x,\omega,\sigma) = e^{i\omega x}G(x,\sigma)$$

where $G(x,\sigma)$ is a normalized Gaussian. Gab is characterized by the following parameters:

• ω denotes the peak tuning spatial frequency which is a function of λ: $\omega = 2\pi/\lambda$, where λ is wavelength.

• σ represents the radius of support which is also a function of λ: $\sigma = (2^\beta+1)/(2^\beta-1)\omega$, where β is the octave bandwidth and usually set to one.

Gab is a complex function, it can be expressed as: $\mathrm{Gab}(x,\omega,\sigma) = \cos\omega x\, G(x,\sigma) + i \sin\omega x\, G(x,\sigma)$. The imaginary part is bandpass, but the real part has a dc component $\int_{-\infty}^{+\infty} \cos\omega x\, G(x,\sigma)dx \neq 0$. In implementation, we apply a slightly altered cosine-Gabor kernel in order to make it bandpass,

$$\mathrm{Gab}_{\cos}(x,\omega,\sigma) = (\cos\omega x - \gamma)G(x,\sigma),$$

where γ is a constant set to $e^{-\omega^2\sigma^2/2}$.

Convolving a 1D image with a complex Gabor filter of fixed λ, the response $R(x)$ is:

$$R(x) = R_{\cos}(x) + i\, R_{sin}(x)$$

where

$$R_{\sin}(x) = \sin\omega x G(x) * I(x)$$

and

$$R_{\cos}(x) = (\cos\omega x - \gamma)G(x) * I(x).$$

The amplitude and the phase of the response are given by:

$$\rho(x) = |R(x)| = \sqrt{R^2_{\sin}(x) + R^2_{\cos}(x)} \qquad (1)$$

$$\phi(x) = \arg(R(x)) = \arctan\left(\frac{R_{\sin}(x)}{R_{\cos}(x)}\right) \qquad (2)$$

The local frequency of $R(x)$ can be defined as the derivative of the phase: $\phi_x(x)$[9], where

$$\phi_x(x) = \frac{R'_{\sin}(x)R_{\cos}(x) - R_{\sin}(x)R'_{\cos}(x)}{R^2_{\sin}(x) + R^2_{\cos}(x)} \qquad (3)$$

Finding Step Edges

In this section we show how the problem of step edge detection can be reduced to the problem of finding appropriate features in phase space.

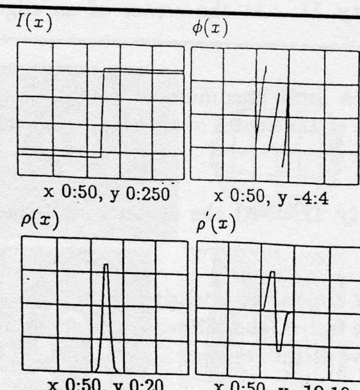

Figure 2: A 1D step edge, phase, amplitude and derivative of amplitude

Step Edge Model

Consider a step edge centered at origin, we define an isolated step edge model as:

$$I(x) = \begin{cases} A_1 & x < 0, \quad A_1, A_2 > 0 \\ A_2 & x > 0, \quad A_1 \neq A_2 \end{cases} \qquad (4)$$

where A_1 and A_2 are the gray-level of the two uniform regions.

Phase and Related Properties Of Step Edges

Consider the edge model defined in (4), and the convolution of the edge with the modified Gabor kernel. A number of useful properties can be shown (proofs are detailed in [8]) based on the local phase and other information of the convolved image.

Property I: At the center of an edge, $|\phi(x)|$ is $\frac{\pi}{2}$.

The type of an edge can be further classified by the sign of the phase which indicates a positive- or negative-going edge.

Property II: At the center of an edge, $\rho(x)$ is nonzero.

In fact, a local maximum of amplitude should be achieved at the center of an edge which can be seen in Figure 2.

Property III: At the center of an edge, $\rho_x(x)$ is zero.

Figure 2 shows the intensity profile of a step edge, its phase from Gabor filtering, the amplitude and its derivative of the response.

Edge Detection

First, as Gabor filters are bandpass filters, λ should be properly chosen (in our implementation, λ usually takes 8) in order to have an appropriate pass frequency. Based on above properties, we can identify step edge candidates by searching for absolute phase value which is or is near (ideal step edges rarely exist in real images) $\pi/2$ in phase space. The distance between phase and $\pi/2$ is measured as $||\phi(x)| - \pi/2|$ and is bounded by ϵ which could be tuned to control the resolution of edges detected. Then we have to check if the detected candidates violate constraints on amplitude or derivative of amplitude. Most of the spurious noise will be eliminated by violating the amplitude constraints. Edges are only labelled for those locations at which all three constraints are satisfied.

Finding Bar-Like Targets Of Particular Width

Bar Model

Assuming a bar of uniform intensity on an uniform gray-level background, we define an isolated bar model centered at x=0 as:

$$I(x) = \begin{cases} A_2 & |x| < \lambda/2, \quad A_1, A_2 > 0 \\ A_1 & |x| > \lambda/2, \quad A_1 \neq A_2 \end{cases} \quad (5)$$

where A_1 and A_2 are the gray-level of background and bar respectively, and λ is the width of the bar.

Phase and Related Properties Of A Bar Of Particular Width

Convolving the bar model defined in (5) with Gabor filters of wavelength λ set to the intended bar width λ_0, a number of properties are derived to characterize bars of particular width.

Property I: At the center of a bar of width $\lambda = \lambda_0$, $\phi(x)$ is zero.

Property II: At the center of a bar of width $\lambda = \lambda_0$, $\rho(x)$ is nonzero.

Property III: At the center of a bar of width $\lambda = \lambda_0$, $\phi_x(x)$ is zero.

Property IV: At the center of a bar of width $\lambda = \lambda_0$, $\rho_x(x)$ is zero.

Bar Detection

In[5], phase and the behavior of its singularity neighborhoods were considered in a Gabor scale-space expansion (the filter output as a function of spatial position and the principal wavelength) of a 1D signal. Let (x_0, λ_0) denote the location of a singularity. The neighborhoods above (below) singular points (above:$\lambda > \lambda_0$, below:$\lambda < \lambda_0$) are characterized by local frequencies that are significantly below (above) the corresponding peak tuning frequency. There exist retrograde regions along which the local frequency is zero, i.e. $\phi_x(x, \lambda) = 0$. In[5], neighbors above or below the singular points (which were characterized by local frequency significantly below or above the peak tuning frequency) were detected by restricting the distance between the local frequency of response and the peak tuning frequency, and neighborhoods spatially adjacent to singular points were detected by applying constraints on local amplitude and its

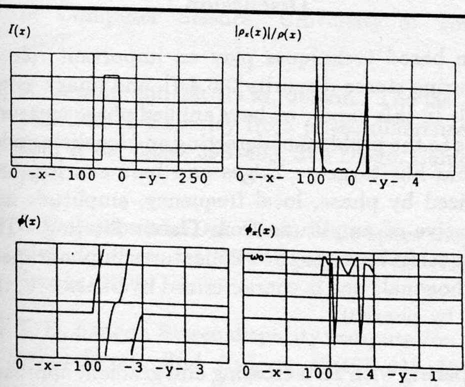

Figure 3: A 1D bar, relative amplitude derivative, phase and local frequency

variation. Similar constraints can be applied in our bar detection scheme. Figure 3 shows the local phase and related structures for an ideal bar. The local frequency $\phi_x(x)$ is roughly ω_0 with wrap around effects as well as retrograde regions (places where $\phi_x(x) = 0$). For the ideal situation ($\lambda = \lambda_0$) a retrograde region corresponds to the exact center of the bar. For more practical situations in which $\lambda \approx \lambda_0$, then the retrograde region may vanish. Nevertheless, the center of a candidate bar is characterized by $\phi(x) = 0$.

In order to be able to trust local phase measurements the following restrictions must be qualified (which is well expressed in [5]):

$$|\phi_x(x) - \omega_0| < \tau_1, \quad |\rho_x(x)|/\rho(x) < \tau_2$$

where τ_1 and τ_2 are constants related to λ_0. The first constraint forces the local frequency of the output of the Gabor filter to agree with the pass frequency of the Gabor. The second constraint requires that (a) there is sufficient energy in the pass region, and (b) the energy is relatively constant over a local region spatially. We can identify potential candidate bars as zero-crossing in $\phi(x)$. If at a position $\phi(x) = 0$, we

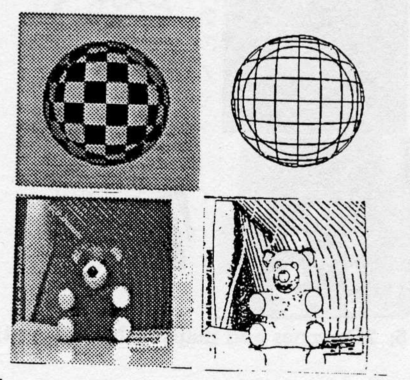

Figure 4: 2D scenes and their edge maps

find that the amplitude constraint is violated then this candidate bar is ignored. If on the other hand the local frequency constraint is violated then checks are made to see if the retrograde region lies within a region of consistent frequency ($\omega \approx \omega_0$) and if the amplitude constraint is satisfied. Locations satisfy all three constraints correspond to bars of exactly the correct width as shown in Figure 3.

For detected bars, the measurements can be rated by how well these constraints are satisfied by the data, i.e. $e = \alpha|\phi_x(x) - \omega_0| + (1 - \alpha)|\rho_x(x)|/\rho(x)$, where α is a parameter weighting the two constraints.

Experimental Results

Detection schemes as described in this paper are one dimensional processes. By applying these processes in both the horizontal and vertical directions and then combining the results, algorithms are available respectively for the localization of edges and bars with horizontal or vertical components of a particular width.

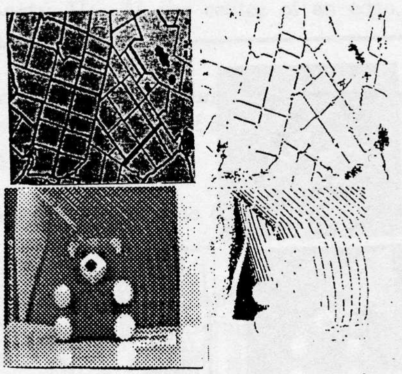

Figure 5: 2D scenes and maps of bars of particular width

Figure 4 shows an input image and the edge map produced by our phase-based edge finding algorithm. It can be seen most of the intensity discontinuities are labelled but there exists aliasing phenomenon in the cluster of edges region. This is due to our isolated edge model and the constraint of Nyquist frequency. To improve the output, multi-edge models have to be defined and the behaviors of interactions between adjacent edges have to be studied. Figure 5 shows input images which contains a number of bar-like feature and shows the combined outputs of the algorithm applied in both the horizontal and vertical directions. Note that in Figure 5 most of the bar like structure in the images have been identified and that certain structures – such as edges and crossings of bars – have not been selected. In addition, bars of widths relatively far from the tuning width have not been reported. In the second bar test image, there exists aliasing phenomenon as in the second edge test image. The problem is due to the same reason as in the edge case.

Discussion

Phase based techniques play an important role in measuring stereo disparity[3,6,4,7], and image velocity [2]. In this paper, we have applied phase measurements to the problem of detecting and localizing edge and bar-like targets. Edges and bars can be characterized by phase, local frequency, amplitude and derivative of amplitude from Gabor filtering. The relationship between the two features in phase space is orthogonal: one is characterized by phase $\pi/2$, the other by phase 0.

Comparing with zero-crossing and gradient approaches, phase based techniques are more robust. They identify and rule out undesired regions and concentrate measurements in regions which contain valid phase measurements. However, as with other feature detection approaches which define a model and derive operators to identify it, the detection mechanism provides necessary, but not sufficient processes for identifying edges and bars. Thus noise may also be present in the edge map while non-bar structures may appear in the bar map. For example, in the bar test image, blobs and text are also identified as bars, therefore, subsequent process must be used to remove these extra structures.

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