

Lecture 7: Image Processing, Feature Detection and Description

7.1 Introduction

Once an autonomous system is able to collect visual information from its surroundings, it must perform a series of operations to develop a representation of the structure and surroundings captured in this raw visual input. This allows the system to interpret its surroundings, and the ability to do so accurately is fundamental to successful execution of downstream autonomous operations such as localization, mapping, and decision-making. In this lecture, several key steps will be outlined which contribute to the extraction of such information from images. This lecture will describe some of the most common steps of the image processing pipeline, including filtering, differentiation, feature detection, and feature description. The core learning objectives of this lecture are as follows:

- Articulate motivation and key concepts of image filtering, and describe several techniques and mathematical operations used to filter and pre-process images;
- Define the concept of image differentiation for a two-dimensional function representation of an image, and describe the central difference method as well as several alternatives for performing said differentiation (e.g. masks);
- Develop the notion of detectors as applied to image feature extraction, and describe two illustrative examples in the form of corner and edge detection;
- Define various alternatives of image feature descriptors and their applications in object detection and matching.

By means of the learning objectives and techniques outlined above, this section will describe a workflow by which raw image data (in the form of pixels and color values) can be transformed into a workable representation of the image. From this representation, local features can be used to make inferences on more complex image properties such as similarity of images, object detection, depth / structure identification, and tracking of objects between frames.

7.2 Image Filtering

We start by considering an image as a function $I: [a, b] \times [c, d] \rightarrow [0, L]$, where $I(x, y)$ represents the grayscale pixel intensity at (x, y) for $a \leq x \leq b$ and $c \leq y \leq d$. Assuming we have a two-dimensional grayscale image, the image is represented as a two-dimensional matrix with r rows and c columns. Each entry is equal to the discretized brightness level; often we use 256 levels, where 0 corresponds to black and 255 to white. (Note that 256 is chosen because it corresponds to the number of levels that can be represented in a single byte.) For a color image, each entry in the matrix would be a vector function with three components, one each for the red, green, and blue color channels.

Image filtering is the process of accepting and rejecting certain frequency components in an image. These filters can be implemented in one of two ways: (1) in the frequency domain or (2) in the spatial domain. In this class we will primarily focus on filters in the spatial domain.

OpenCV implements a number of image filtering algorithms. Read more about them [here](#).

7.2.1 Spatial Filters

A spatial filter consists of:

1. A neighborhood S_{xy} of pixels around the point (x, y) under examination
2. A predefined operation F that is performed on the image pixels within S_{xy}

Spatial filters can be linear or non-linear. In this class, we will focus on linear spatial filters, given by the equation 7.1 below.

$$I'(x, y) = F \circ I = \sum_{i=-n}^n \sum_{j=-m}^m F(i, j) I(x + i, y + j) \quad (7.1)$$

In equation 7.1, I' represents the filtered image, F represents the filter mask (sometimes called the kernel or window), and I represents the original image. The filter mask F is of size $(2n + 1) \times (2m + 1)$, where each entry represents the weighting of a particular neighbor pixel from the original image.

We apply this filter mask to every pixel (x, y) by multiplying each intensity value in the neighborhood of (x, y) by a certain weight $F(i, j)$ in order to get to the filtered image I' . This procedure is referred to as a *correlation* with the kernel F , and is illustrated in figure 7.1.

As we apply this filter, we have to decide what to do at the boundaries of our image. There are a number of options, including padding the image, cropping it, extending it, or wrapping it. However, as images are generally quite large, the exact treatment chosen for the edges does not vary the final result significantly.

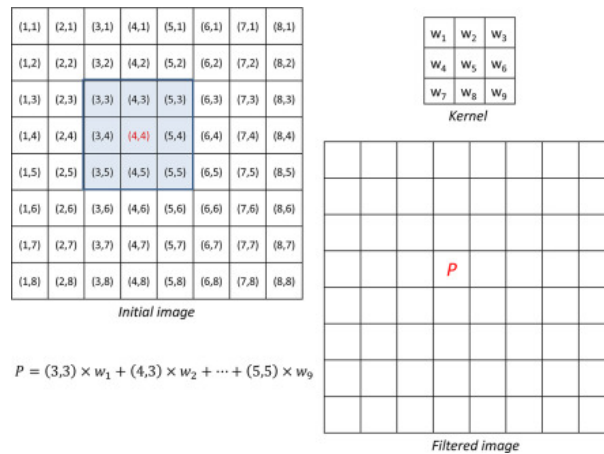


Figure 7.1: Correlation of initial image with a kernel to produce a filtered image

7.2.1.1 Moving Average

As an example of a linear spatial filter, the moving average filter returns the average of the pixels in the mask. It achieves a smoothing effect by removing sharp features. For example, for a *normalized* 3×3 mask,

$$F = \frac{1}{9} \begin{bmatrix} 1 & 1 & 1 \\ 1 & 1 & 1 \\ 1 & 1 & 1 \end{bmatrix}$$

This filter is commonly used to reduce noise and smooth or blur an image, as seen in figure 7.2. The *normalization* is done so that the overall brightness of the image remains constant.

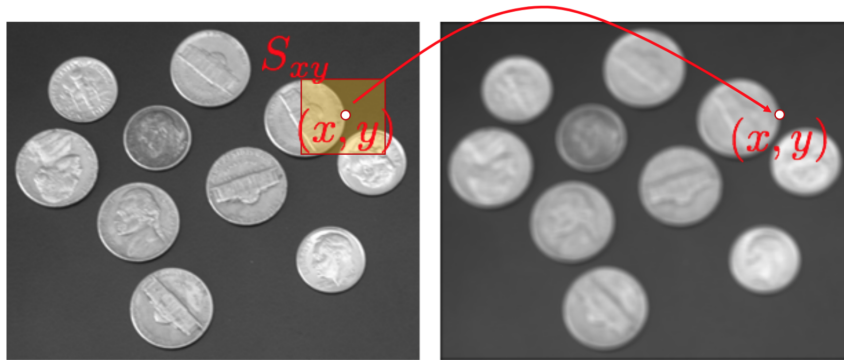


Figure 7.2: Example of a moving average filter

Read more about the OpenCV implementation of this [here](#).

7.2.1.2 Gaussian Smoothing

Another linear spatial filter, the Gaussian filter, is often preferred over a simple moving average filter because it gives higher weights to pixels closer to the center of the filter and lower weights to those along the edge. The Gaussian smoothing function with variance σ^2 is given in equation 7.2 below.

$$G_{\sigma}(x, y) = \frac{1}{2\pi\sigma^2} \exp\left(-\frac{x^2 + y^2}{2\sigma^2}\right) \quad (7.2)$$

The function is sampled about its center to obtain the mask. For example, for a normalized 3×3 mask with $\sigma = 0.85$,

$$G = \frac{1}{16} \begin{bmatrix} 1 & 2 & 1 \\ 2 & 4 & 2 \\ 1 & 2 & 1 \end{bmatrix}$$

Read more about the OpenCV implementation of this [here](#).

7.2.1.3 Convolution

Convolution is a linear filter that is similar to correlation, but has reverse image indices. Correlation and convolution are identical when the filter is symmetric. The convolution equation is shown in 7.3.

$$I'(x, y) = F * I = \sum_{i=-n}^n \sum_{j=-m}^m F(i, j) I(x - i, y - j) \quad (7.3)$$

Convolution is associative, meaning that $F * (G * I) = (F * G) * I$. We commonly use this property when trying to smooth an image and then take the derivative of the result to obtain the gradient. Instead of doing these sequentially, we can combine the two operations into one by first convolving the derivative filter with our smoothing filter (e.g. a Gaussian filter), then convolving the resulting filter with the image. This second approach is advantageous because it is less computationally intensive.

7.2.1.4 Separable Masks

A mask is separable if it can be broken down into the convolution of two kernels $F = F_1 * F_2$. If a mask is separable into “smaller” masks, then it is often cheaper to apply F_1 followed by F_2 , rather than by F directly. One special case of this is when the mask can be represented as outer product of two vectors (meaning it is equivalent to the 2D convolution of those two vectors). If the mask is of shape $M \times M$, and the input image has size $w \times h$, then the computational complexity of directly performing the convolution is $O(M^2wh)$. However, if one were to separate the mask into its component vectors and convolve these components with the input image, the computational cost would be $O(2Mwh)$, which is linear, not quadratic in M .

The moving average mask can be separated as shown below.

$$F = \frac{1}{9} \begin{bmatrix} 1 & 1 & 1 \\ 1 & 1 & 1 \\ 1 & 1 & 1 \end{bmatrix} = \frac{1}{9} \begin{bmatrix} 1 \\ 1 \\ 1 \end{bmatrix} \begin{bmatrix} 1 & 1 & 1 \end{bmatrix}$$

The Gaussian mask is also separable because the exponential function can be separated out. The Gaussian smoothing separable mask is shown below in equation 7.4.

$$\begin{aligned} G_{\sigma}(x, y) &= \frac{1}{2\pi\sigma^2} \exp\left(-\frac{x^2 + y^2}{2\sigma^2}\right) \\ &= \frac{1}{\sqrt{2\pi}\sigma} \exp\left(-\frac{x^2}{2\sigma^2}\right) \frac{1}{\sqrt{2\pi}\sigma} \exp\left(-\frac{y^2}{2\sigma^2}\right) \\ &= g_{\sigma}(x) \cdot g_{\sigma}(y) \end{aligned} \quad (7.4)$$

Decomposing a mask into its separable components does not alter the results but can drastically improve the computational speed of your code.

7.3 Image Differentiation

Taking the derivative of an image is similar to differentiating a function with a two-dimensional domain. On a basic level, the derivative of an image represents changes in pixel intensity in both the vertical and

horizontal direction. Because images are discrete functions, the traditional method for differentiating continuous functions can not be used. One popular method to differentiate an image is known as the central difference method; the equations for this method are shown below in equation 7.5. These equations find the change in intensity between the neighboring pixels.

$$\begin{aligned}\frac{\partial I}{\partial x} &= \frac{I(x+1, y) - I(x-1, y)}{2} \\ \frac{\partial I}{\partial y} &= \frac{I(x, y+1) - I(x, y-1)}{2}\end{aligned}\tag{7.5}$$

Here, I is the intensity of the image, and x and y define the location of the pixel of interest. Note that applying a normalization factor to these equations does not effectively change the result, as the background intensities will be scaled by the same factor. The derivative with respect to x is the derivative in the horizontal direction, and the derivative with respect to y is in the vertical direction. The central difference method looks at the neighboring pixels on both sides of the pixel of interest. It is also valid to just consider one side of each pixel to calculate the derivative, for example $\frac{\partial I}{\partial x} = I(x+1, y) - I(x, y)$. While this method would be correct, using both neighboring sides is generally better at estimating the derivative right at the pixel of interest.

It is also possible to differentiate an image using convolution operations, such as with a Sobel mask. Sobel masks work similarly to the masks discussed earlier in this lecture. The Sobel masks for the x and y direction are given below.

$$S_x = \begin{bmatrix} 1 & 0 & -1 \\ 2 & 0 & -2 \\ 1 & 0 & -1 \end{bmatrix}, \quad S_y = \begin{bmatrix} 1 & 2 & 1 \\ 0 & 0 & 0 \\ -1 & -2 & -1 \end{bmatrix}$$

Sobel masks are similar to the central difference method described above in that both approaches use the intensity of neighboring pixels to find the derivative, but Sobel masks use more neighboring pixels when calculating the derivative, applying a weighting factor to each pixel. We can see that more weight is given to the pixels directly adjacent to the pixel of interest.

For example, S_x weights the rows above and below the row of interest to calculate the horizontal derivative, and S_y weights the columns to the left and the right of the column of interest to find the vertical derivative. In essence, the S_x operator takes the central difference of the the row of interest, as well as the rows above and below the pixel location, and then takes a weighted average of those central differences to make the differentiation more robust.

7.3.1 Similarity Measures

Filtering can also be used to find similar features in different images. Two useful examples of similarity measures are the sum of absolute differences (SAD) and the sum of squared differences (SSD). The equations for each are given below in (7.6) and (7.7), respectively.

$$SAD = \sum_{i=-n}^n \sum_{j=-m}^m |I_1(x+i, y+j) - I_2(x'+i, y'+j)|\tag{7.6}$$

$$SSD = \sum_{i=-n}^n \sum_{j=-m}^m [I_1(x+i, y+j) - I_2(x'+i, y'+j)]^2\tag{7.7}$$

In these equations, x and y refer to a point in image I_1 , and x' and y' refer to a point in image I_2 . The width and height of the patch, in pixels, are then $H = 2n + 1$ and $W = 2m + 1$. SAD and SSD tend not to be very robust, but they do provide a starting point for comparing image features.

7.4 Image Feature Extraction

A local feature on an image can often also be referred to as an interest point, interest region, or keypoint - it is an image pattern where the intensity, color or texture differs from its immediate neighborhood. Often times, such as in medical image processing or automotive applications, local features have semantic interpretations, such as blobs corresponding to blood cells in medical images or edges corresponding to the lane of the road. There are also some features that do not possess semantic content but their locations can be found consistently and robustly over time, which is valuable for uses such as feature tracking, camera calibration, 3D reconstruction, image mosaicing and panorama stitching. In some cases, the location of the features does not matter either; for applications such as scene classification, texture analysis, video mining, and image retrieval, only the number of feature matches is important. This section discusses the basic concepts of some local feature extractors (detectors and descriptors), and their desired properties.

7.4.1 Detectors

Detectors detect local features. The most common detectors are edge detectors, corner detectors and blob detectors.

7.4.1.1 Edge Detection

Introduction

Let us define an edge as “a region in an image where there is a significant change in intensity values along one direction, and negligible change along the orthogonal direction”. In one dimension, an edge corresponds to a point where there is a sharp change in intensity, or more explicitly, a large first derivative and a small second derivative. Many edge detectors rely on differentiating images and looking for spikes in the derivative.

Some criteria necessary for robust edge detection include accuracy, localization, and single response. To elaborate, good accuracy implies few false positives or negatives (missed edges). Good localization implies that the detected edge should be exactly where the true edge is in the image. A single response implies one edge is detected for each real edge. For example, one real edge should not be detected as two separate edges. Noise and discretization may challenge our ability to detect edges.

Most edge detection methods rely on two key steps: smoothing and differentiation. Differentiation is performed in both the vertical and horizontal directions to find locations with high intensity gradients in just one of the two directions. However, differentiation alone is vulnerable to false positives due to image noise, which may be gaussian additive noise or otherwise such as salt & pepper noise (where random pixels jump to either complete white or complete black) [1]. In order to lower the noise, many algorithms will smooth the image before differentiating it. The next section explores edge detection further.

Techniques

In this part we will discuss classic edge detection techniques. They involve the use of convolution with a

kernel to extract edges. For example, differentiating every point in our signal should only give non zero values (or at least high values) at each edge, allowing us to sort them easily. However we will see that this is not always the case as our signal/image is usually not as smooth as we would like it to be.

Let us first explore the 1D case to understand the principle of edge detectors and how they behave under high noise. For example, looking at 7.3, we see that simply differentiating the signal without performing any sort of filtering will yield a completely useless result, as noise causes random values of the derivative at every point. There is no detection threshold that will allow us to detect edges from this differentiated signal.

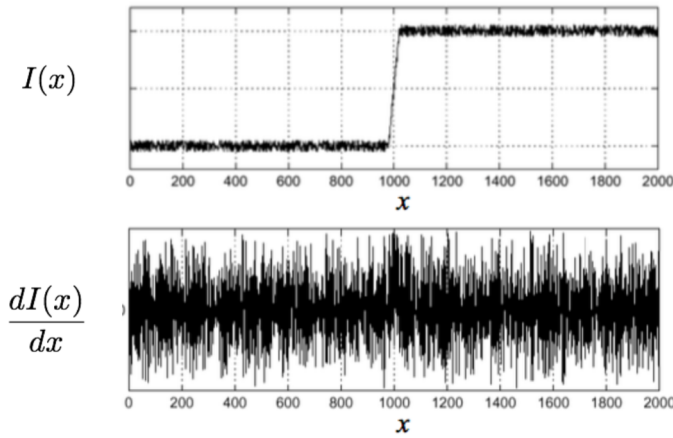


Figure 7.3: Differentiation of a noisy signal

We can remedy this problem by filtering the signal. For example we may use a Gaussian filter to apply a smoothing mask, the result of which can be differentiated to identify edges (by identifying the highest value or the point where the second derivative cancels). To do so, we perform the following convolutions:

$$s(x) = g_{\sigma}(x) * I(x)$$

$$s'(x) = \frac{d}{dx} * s(x)$$

Where I is the original signal, g_{σ} is the Gaussian, and s' is the final mask. The performance of such a procedure may be seen in 7.4.

One issue with this method is that it requires that we compute two convolutions on our image, which can be computationally expensive. It is possible to exploit the associativity of the convolution to perform the same transformation with a single convolution:

$$s' = \frac{d}{dx} * (g_{\sigma} * I) = \left(\frac{d}{dx} * g_{\sigma} \right) * I$$

Therefore the function $g'_{\sigma} = \frac{d}{dx} * g_{\sigma}$ may be used for much faster computation. An illustration of this process may be seen in 7.5.

Now we might take inspiration from this 1D case to design a 2D edge detector. Let G_{σ} be the two dimensional Gaussian distribution (i.e. $G_{\sigma}(x, y) = \frac{1}{2\pi\sigma^2} \exp\left(-\frac{x^2+y^2}{2\sigma^2}\right)$). An illustration of this function and its derivative may be found in 7.6.

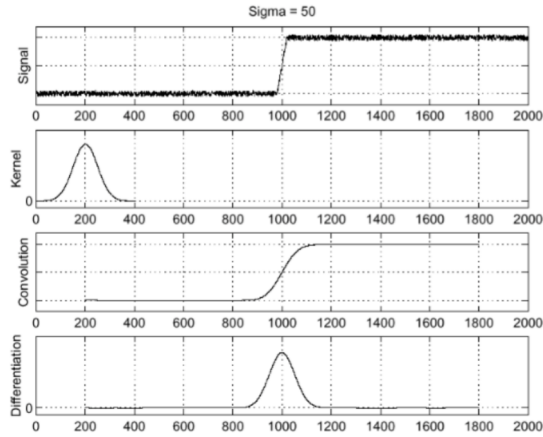


Figure 7.4: Edge detection through convolution with Gaussian kernel, followed by differentiation

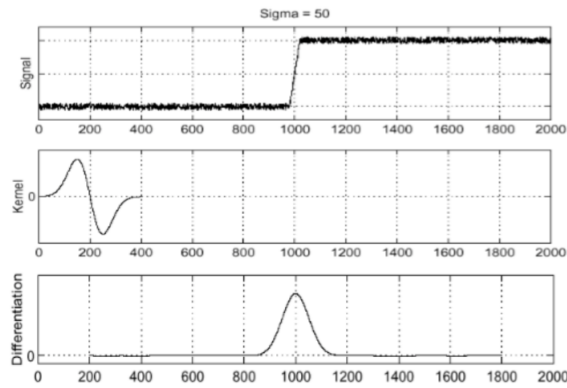


Figure 7.5: Edge detection through convolution with a differentiated Gaussian kernel

The gradient of the smoothed image may be written as:

$$\nabla S = \begin{bmatrix} \frac{\partial}{\partial x} * G_{\sigma} * I \\ \frac{\partial}{\partial y} * G_{\sigma} * I \end{bmatrix} = \begin{bmatrix} G_{\sigma,x} * I \\ G_{\sigma,y} * I \end{bmatrix} = \begin{bmatrix} S_x \\ S_y \end{bmatrix}$$

We notice that once again we are able to reduce the number of convolutions to 1 by building the partial derivatives of the Gaussian: $G_{\sigma,x}$ and $G_{\sigma,y}$. As in the 1D case, our next step is to check $|\nabla S| = \sqrt{S_x^2 + S_y^2}$ against an aptly chosen threshold to detect edges. We may additionally filter out points that are above the threshold but not local maxima to guarantee thin edges.

Finally, an application of this method on a picture classically used to demonstrate image processing techniques may be found in 7.7.

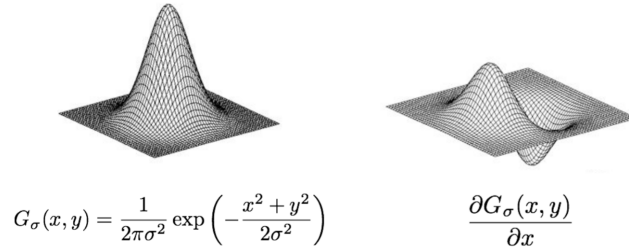


Figure 7.6: 2D Gaussian function

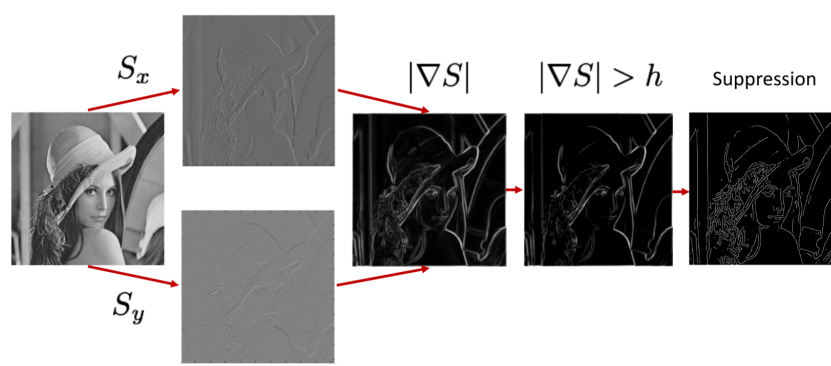


Figure 7.7: Classic example of 2D edge detection

7.4.1.2 Corner Detector

Corner

A corner in an image is defined as an intersection of two or more edges, or as defined by Moravec [2], a point where there is a large intensity variation in every direction. As shown in Fig. 7.8, for a window which is centered at a pixel in a region of uniform intensity (a “flat” region), its adjacent windows in all directions will be identical. For a window centered at a pixel on an edge, the adjacent windows will look the same except for the ones in the direction perpendicular to the edge. For a window centered at a pixel on a corner, the adjacent windows in any direction will look different.

Moravec’s method identifies a corner where the Sum of Squared Difference (SSD) is at its local maxima. The SSD between image patch centered on pixel coordinate (u, v) and the image patch offset by (x, y) is given by:

$$SSD = \sum_{i=-n}^n \sum_{j=-m}^m [I_1(x+i, y+j) - I_2(x'+i, y'+j)]^2 \quad (7.8)$$

where I denotes the intensity of a grayscale image.

Desired Properties of Corner Detectors

The most important desired properties of corner detectors are repeatability and distinctiveness. Having detectors with “repeatability” means that the same features taken at the same scene under different view-point and illumination conditions can be found in multiple images, which requires the features to be invariant to geometric and photometric transformations. Having detectors with “distinctiveness” means the information carried by the patch surrounding the keypoints are highly distinctive, therefore a reli-

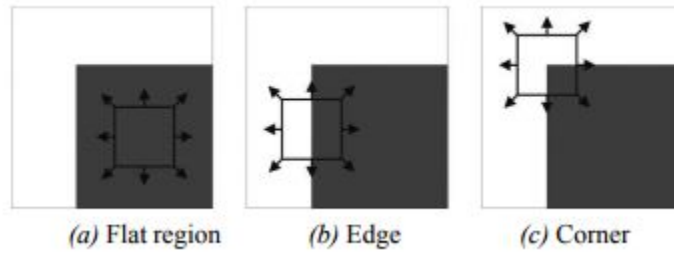


Figure 7.8: a) “Flat” region: no change in all directions. b) “Edge”: no change along the edge direction. c) “Corner”: significant changes in all directions. [3]

able correspondence can be established, and feature points can be distinguished and matched. Good repeatability and distinctiveness are both desirable for point matching and applications such as panorama stitching and 3D reconstruction.

Harris Corner Detector

Instead of the shifting windows, the Harris corner detector [4] uses partial derivatives of the SSD which improves upon Moravec’s corner detector.

Harris and Stephens first approximated $I(u + x, v + y)$ with a first-order Taylor expansion; the SSD can be expressed as follows:

$$SSD(x, y) \approx \sum_u \sum_v (I_x(u, v)x + I_y(u, v)y)^2 \quad (7.9)$$

where I_x and I_y are the partial derivatives in the x, y direction respectively. The quadratic form in Eq. 7.9 can be written in a matrix form:

$$SSD(x, y) \approx \begin{bmatrix} x & y \end{bmatrix} M \begin{bmatrix} x \\ y \end{bmatrix} \quad (7.10)$$

where M is the second moment matrix

$$M = \begin{bmatrix} \sum \sum I_x^2 & \sum \sum I_x I_y \\ \sum \sum I_x I_y & \sum \sum I_y^2 \end{bmatrix} \quad (7.11)$$

Because M is symmetric, M can be decomposed as:

$$M = R^{-1} \begin{bmatrix} \lambda_1 & 0 \\ 0 & \lambda_2 \end{bmatrix} R \quad (7.12)$$

where λ_1 and λ_2 are the eigenvalues of M .

As shown in Fig. 7.9, if both λ_1 and λ_2 are small, the change in intensity in both directions is small, and therefore a flat region can be identified; if both λ_1 and λ_2 are large, indicating a large SSD in both directions, then a corner is detected; if one eigenvalue is significantly higher than the other, the SSD is dominant in one direction, which indicates an edge. In order to reduce the complexity of the computation (i.e., avoiding calculation of eigenvalues), Harris and Stephens introduced the “cornerness function,” C , so that only the determinant and the trace of matrix M need to be computed.

$$C = \lambda_1 \lambda_2 - \kappa (\lambda_1 + \lambda_2)^2 = \det(M) - \kappa \cdot \text{trace}^2(M) \quad (7.13)$$

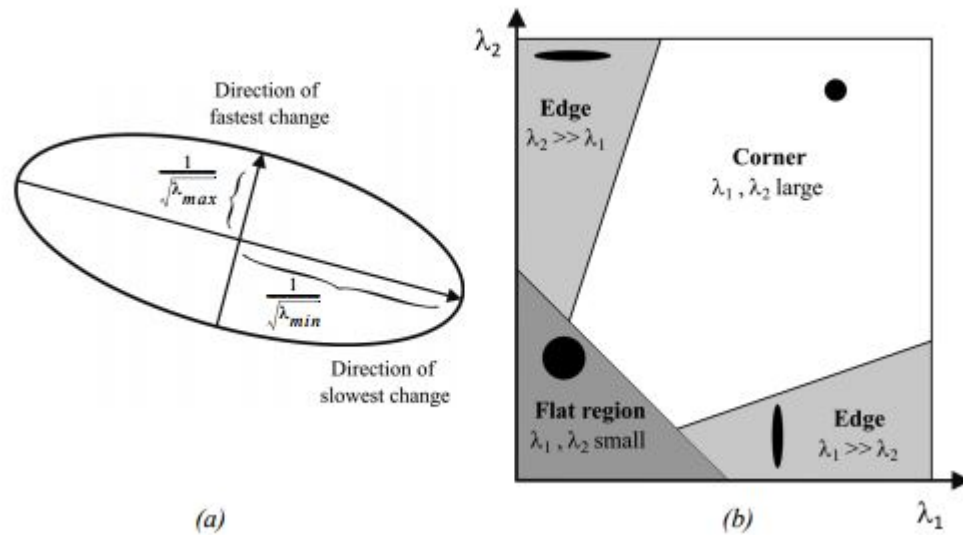


Figure 7.9: a) Visualization of direction of the fastest and slowest change of intensity built from matrix M . b) Harris and Stephens' classification of corners and edges [3]

Here κ is an empirically determined tunable sensitivity parameter, usually in the range of 0.04–0.15. The Harris corner detector's last step is then to extract local maxima of the cornerness function using non-maxima suppression (an algorithm that preserves only the maxima in a region).

The Harris corner detector is invariant to 2D rotations, as the eigenvalues of the second moment matrix M don't change under pure rotation. The Harris corner detector is also invariant to affine intensity changes ($I' = aI + b$) because the eigenvalues and the cornerness function are rescaled by a constant factor and the locations of local maxima remain unchanged. However, the Harris corner detector is not invariant to geometric affine transforms and image scaling due to the discretization of the image into pixels. Under a geometric affine transform, the neighborhood of the feature along x and y directions can be distorted, varying the curvature differently in the x and y directions. When the image is scaled, the region of the corner detector may become too large or too small. For example, it is possible for a corner to be identified as a corner at a lower scale, but an edge at a higher scale.

7.4.2 Descriptors

Descriptors describe keypoints (local features) to be compared across images or used for object detection or matching. Like the detectors, it is also desirable for descriptors to be repeatable and distinct. A naive descriptor is an $n \times m$ window of pixel intensities centered at a keypoint, which can be normalized to be illumination invariant; however, it is not invariant to pose and scale, and is poorly distinctive.

7.4.2.1 SIFT

SIFT is short for Scale Invariant Feature Transform, invented in 1999 by Lowe [5]. SIFT not only incorporates all the properties of the scale-affine-invariant Harris, but is also extremely distinctive and robust to

image noise, small illumination variations, and viewpoint changes. It is known for its high repeatability and high matching rate even in very challenging conditions, and it has many applications in object, gesture and face recognition, robotic perception and 3D modeling. SIFT features are essentially local distributions of the image gradient around keypoints with highly informative content. The following briefly introduces the main steps of the SIFT algorithm. More details can be found in [5].

1. Scale-space extrema detection: Keypoints are detected by searching for stable features across the scale space (a continuous function of scale). The stable keypoint locations are identified by computing the difference of Gaussian (DoG) of two nearby scale space image produced from repeatedly convolving Gaussians with the initial image, and selecting the local extrema where the sample point is the largest or smallest among its eight neighbors in the current image and nine neighbors in the scale above and below.
2. Keypoint localization: The keypoint localization step fits the nearby data for location, orientation, scale and ratio of principal curvatures around keypoints candidates, and rejects the ones that are below some contrast threshold or poorly localized along an edge.
3. Orientation assignment: This step assigns an orientation to a keypoint as the peak in the histogram of gradient orientation in the neighborhood of the keypoint. The keypoint descriptor is then represented relative to the dominant orientation assigned, which allows the descriptor to be rotation invariant. In the case when there are multiple peaks that are more than 80% of the highest peak, multiple keypoints will be created all additional peaks, at the same location but with different assigned orientations.
4. Keypoint descriptor: The previous steps define local image regions by location, scale and orientation, and this step computes a highly distinctive and repeatable descriptor for this local image region. Each keypoint descriptor is built by stacking gradient histogram with 8 orientation bins for each 4×4 subregions of the neighboring region of the keypoints, and is therefore $4 \times 4 \times 8 = 128$ in length. The length of keypoint descriptors can be changed by tuning the block size and orientation bin size; however, the 128 element vector is empirically determined to be the most robust to image variations.

References

- [1] S. E. S. Jayaraman and T. Veerakumar, *Digital Image Processing*. Tata McGraw-Hill Education, 2009.
- [2] H. P. Moravec, "Towards automatic visual obstacle avoidance," in *5th International Joint Conference on Artificial Intelligence*, 1977.
- [3] R. Siegwart, I. Nourbakhsh, and D. Scaramuzza, *Introduction to Autonomous Mobile Robots*. The MIT press, 2011.
- [4] C. Harris and M. Stephens, "A combined corner and edge detector," in *the 4th Alvey Vision Conference*, 1988.
- [5] D. G. Lowe, "Distinctive image features from scale-invariant keypoints," *International Journal of Computer Vision*, vol. 60, no. 2, p. 91, 2004.

Contributors

Winter 2019: Jennifer Villa, Thurston Brevett, Kevin Li, Anand Natu

Winter 2018: Peggy Wang, Molly Zhang, Michael Thompson, Pierre Lachevre, Cuthbert Sun, Quint Underwood