The environment
Camera as sensor

- Image and signal processing.

Implementation:
- OpenCV for processing the Image signals.
- Other libraries for processing 1D signals.
What is an image?

We get this as the input data

Source: A. Efros
Ashutosh Saxena
What is an image?

- A grid of intensity values

(common to use one byte per value: 0 = black, 255 = white)
What is an image?

- We can think of a (grayscale) image as a function, $f$, from $\mathbb{R}^2$ to $\mathbb{R}$:
  - $f(x,y)$ gives the intensity at position $(x,y)$

A digital image is a discrete (sampled, quantized) version of this function.
Image transformations

- As with any function, we can apply operators to an image

\[ g(x, y) = f(x, y) + 20 \]

\[ g(x, y) = f(-x, y) \]

- We’ll talk about a special kind of operator, *convolution* (linear filtering)
ID signal

<table>
<thead>
<tr>
<th></th>
<th>255</th>
<th>200</th>
<th>178</th>
<th>100</th>
<th>74</th>
<th>67</th>
<th>71</th>
<th>101</th>
<th>120</th>
<th>180</th>
<th>211</th>
<th>240</th>
</tr>
</thead>
</table>

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Question: Noise reduction

Given a camera and a still scene, how can you reduce noise?

Take lots of images and average them!
What’s the next best thing?

Source: S. Seitz
Image filtering

- Modify the pixels in an image based on some function of a local neighborhood of each pixel

Local image data

<table>
<thead>
<tr>
<th>10</th>
<th>5</th>
<th>3</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>5</td>
<td>1</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
<td>7</td>
</tr>
</tbody>
</table>

Some function

Modified image data

7

Source: L. Zhang
Linear filtering

- One simple version: linear filtering (cross-correlation, convolution)
  - Replace each pixel by a linear combination of its neighbors
- The prescription for the linear combination is called the "kernel" (or "mask", "filter")

\[
\begin{array}{ccc}
10 & 5 & 3 \\
4 & 6 & 1 \\
1 & 1 & 8 \\
\end{array}
\quad \begin{array}{ccc}
0 & 0 & 0 \\
0 & 0.0 & 0 \\
0 & 5.0 & 0.5 \\
\end{array}
\quad \begin{array}{cccc}
\text{Local image data} & \text{kernel} & \text{Modified image data} \\
\end{array}
\]

Source: L. Zhang
Cross-correlation

Let $F$ be the image, $H$ be the kernel (of size $2k+1 \times 2k+1$), and $G$ be the output image.

\[
G[i, j] = \sum_{u=-k}^{k} \sum_{v=-k}^{k} H[u, v] F[i + u, j + v]
\]

This is called a **cross-correlation** operation:

\[
G = H \otimes F
\]
Convolution

- Same as cross-correlation, except that the kernel is “flipped” (horizontally and vertically)

\[ G[i, j] = \sum_{u=-k}^{k} \sum_{v=-k}^{k} H[u, v] F[i - u, j - v] \]

This is called a convolution operation:

\[ G = H \ast F \]

- Convolution / cross-correlation are commutative and associative
Convolution

Adapted from F. Durand
Mean filtering

\[
H \ast F = G
\]
Mean Filtering: 1-D

One can also apply convolution to 1D signals.

\[ F = [0, 10, 12, 20, 8, 12, 0] \]
\[ H = [0.25, 0.5, 0.25] \]
\[ G = ? \]
Linear filters: examples

Original

\[ \begin{bmatrix} 0 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 0 \end{bmatrix} \]

Identical image

Source: D. Lowe
Linear filters: examples

Original

\[
\begin{bmatrix}
0 & 0 & 0 \\
1 & 0 & 0 \\
0 & 0 & 0 \\
\end{bmatrix}
\]

= Shifted left By 1 pixel

Source: D. Lowe
Linear filters: examples

Original

 Blur (with a mean filter)

Source: D. Lowe
Linear filters: examples

Original * \begin{pmatrix}
0 & 0 & 0 \\
0 & 2 & 0 \\
0 & 0 & 0 \\
\end{pmatrix} - \frac{1}{9} \begin{pmatrix}
1 & 1 & 1 \\
1 & 1 & 1 \\
1 & 1 & 1 \\
\end{pmatrix} = \text{Sharpening filter (accentuates edges)}

Source: D. Lowe
Gaussian Kernel

\[ G_\sigma = \frac{1}{2\pi\sigma^2} e^{-\frac{x^2+y^2}{2\sigma^2}} \]

Source: C. Rasmussen
Mean vs. Gaussian filtering

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Gaussian noise

\[ F[x, y] + \mathcal{N}(0, 5\%) \]

\[ \sigma = 1 \text{ pixel} \quad \sigma = 2 \text{ pixels} \quad \sigma = 5 \text{ pixels} \]

Smoothing with larger standard deviations suppresses noise, but also blurs the image.
Outliers noise – Gaussian blur

- What’s wrong with the results?
Alternative idea: Median filtering

- A **median filter** operates over a window by selecting the median intensity in the window.

- Is median filtering linear?

Source: K. Grauman
Median filter

- What advantage does median filtering have over Gaussian filtering?

Source: K. Grauman
Salt & pepper noise – median filtering

$p = 10\%$

$\sigma = 1$ pixel

$\sigma = 2$ pixels

$\sigma = 5$ pixels

3x3 window

5x5 window

7x7 window
Questions?
Edge Detection
Edge detection

- Convert a 2D image into a set of curves
  - Extracts salient features of the scene
  - More compact than pixels
Characterizing edges

- An edge is a place of rapid change in the image intensity function

Source: L. Lazebnik

- Edges correspond to extrema of derivative
Effects of noise

Noisy input image

\[ f(x) \]

\[ \frac{d}{dx} f(x) \]

Where is the edge?

Source: S. Seitz
Ashutosh Saxena
Solution: smooth first

To find edges, look for peaks in $\frac{d}{dx}(f \ast h)$

Source: S. Seitz

Ashutosh Saxena
Differentiation is convolution, and convolution is associative:

\[ \frac{d}{dx} (f \ast h) = f \ast \frac{d}{dx} h \]

This saves us one operation:

Source: S. Seitz

Ashutoshi Saxena
2D edge detection filters

Gaussian

\[ h_\sigma(u, v) = \frac{1}{2\pi\sigma^2} e^{-\frac{u^2+v^2}{2\sigma^2}} \]

derivative of Gaussian \((x)\)

\[ \frac{\partial}{\partial x} h_\sigma(u, v) \]
Derivative of Gaussian filter

$x$-direction

$y$-direction
The Sobel operator

- Common approximation of derivative of Gaussian
Sobel operator: example
Questions?
Finding Objects

- Background subtraction
Feature extraction: Corners and blobs
Desirable properties in the features

Distinctiveness:

◦ can differentiate a large database of objects

Efficiency

◦ real-time performance achievable
Example of features

A laundry list:

- Corner / edge detectors
- SIFT features
- Output of various filters…
Feature Matching

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Feature Matching

Multiple View Geometry in Computer Vision

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Metric for similarity?

- Vector $x_i$ and $x_j$.
- What is the distance between them?
Matching using distance between the features

Find features that are invariant to transformations
- geometric invariance: translation, rotation, scale
- photometric invariance: brightness, exposure, …

Feature Descriptors

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Object recognition (David Lowe)
Image matching

by Diva Sian

by swashford

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Harder case

by Diva Sian

by scgbt

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Harder still?

NASA Mars Rover images

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How to match features?

- Robustness?

Projects

- Project proposals due **Feb 15**.
  - Brief description of the projects on Thursday lecture.
  - Choose a Topic and a Robot.

- Good time to setup a meeting with the instructor next week.
Questions?