TDI2131 Digital Image Processing

Digital Image Fundamentals
Lecture 2

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Some portions of content adapted from Zhu Liu, AT&T Labs. Most figures from Gonzalez/Woods
Lecture Outline

- Course Information
- Elements of Visual Perception
- Image Acquisition & Representation
- Image Sampling & Quantization
- Basic Relationships Between Pixels
Some Announcements

• Consultation Hours: Wednesdays, 2-6pm
• Matlab software
• This course:
  – Understanding of concepts -> Application of concepts
  – Will go easy on math, but additional knowledge in math can be valuable
Human Vision System

• To understand image processing – consider first our human vision system!

• Observe and evaluate images in our own biological system to avoid misinterpretation of how images are formed
Some questions to ponder...

- What *intensity differences* can we distinguish?
- What is the spatial *resolution* of our eye?
- How accurately do we estimate and compare *distances and areas*?
- How do we sense *colors*?
- By which *features* can we detect and distinguish objects?
Let's put you through a test...
Test Images for Distances and Area Estimation

(a) Parallel lines with up to 5% difference in length
(b) Circles with up to 10% difference in radius
(c) The vertical line appears longer but actually has the same length as the horizontal line
(d) Deception by perspective: the upper line appears longer than the lower one but actually have the same length

Did your eyes fail you?
Structure of the Human Eye

- Shape is nearly a sphere
- Average diameter = 20 mm
- 3 membranes:
  - Cornea & Sclera – outer cover
  - Choroid
  - Retina – enclose the eye
Structure of the Human Eye

- **Cornea**
  - Tough, transparent tissue, covers the anterior surface of the eye

- **Sclera**
  - Opaque membrane, encloses the remainder of the optic globe

- **Choroid**
  - Network of blood vessels, heavily pigmented
Structure of the Human Eye

- **Lens**
  - Both infrared & ultraviolet light are absorbed by proteins within the lens – excessive amounts can damage eye

- **Retina**
  - Innermost membrane of the eye which lines inside of the wall's entire posterior portion. When properly focused, light from an object is *imaged* or “projected” on the retina.
Receptors

• Vision is afforded by the distribution of discrete light receptors over the surface of the retina

• Receptors are divided into 2 classes:
  – Cones
  – Rods
Cones

- 6-7 million, located primarily in the central portion of the retina (the fovea, muscles controlling the eye rotate the eyeball until the image falls on the fovea)
- Highly sensitive to colour
- Each is connected to its own nerve and thus human can resolve fine details
- Cone vision is called photopic vision (allows color perception) or bright-light vision
Rods

- 75-150 million, distributed over the retina surface
- Several rods are connected to a single nerve end – reduce the amount of detail discernible
- Serve to give a general, overall picture of field of view
- Sensitive to low levels of illumination
- Rod vision is called **scotopic vision** or dim-light vision
Eye vs. Camera

<table>
<thead>
<tr>
<th>Camera components</th>
<th>Eye components</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lens</td>
<td>Lens, cornea</td>
</tr>
<tr>
<td>Shutter</td>
<td>Iris, pupil</td>
</tr>
<tr>
<td>Film</td>
<td>Retina</td>
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<tr>
<td>Cable to transfer images</td>
<td>Optic nerve send the info to the brain</td>
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</tbody>
</table>
The shape of the lens is controlled by tension in the fibres of the ciliary body.
Brightness Adaptation and Discrimination

- The total range of intensity levels it can discriminate simultaneously is rather small compared with the total adaptation range.
- $B_a$ is a brightness adaptation level. The short intersecting curve represents the range of subjective brightness that the eye can perceive when adapted to this level.
Contrast Sensitivity

1. How much can the eye discriminate between changes in brightness at any specific adaptation level?
2. \( I \) is uniformly illumination on a flat area large enough to occupy the entire field of view.
3. \( \Delta I_c \) is the change in the object brightness required to just distinguish the object from the background.

\[
\text{Weber's ratio: } \frac{\Delta I_c}{I} \\
\text{Good brightness discrimination } \Rightarrow \Delta I_c I \\
\text{Bad brightness discrimination } \Rightarrow \Delta I_c / I \text{ is large.}
\]
Weber Ratio

- Hard to distinguish discrimination in a bright area, but easier to discriminate in a dark area
- Which discriminates better under low levels of illumination, rods or cones? What does this mean?
Brightness vs. Function of Intensity

- Brightness is not a simple function of intensity
- Our visual system tends to undershoot or overshoot around the region boundaries of different intensities
- In theory, intensity is constant – but we perceive brightness as strongly scalloped near the boundaries
Mach Band Pattern

- Are the levels of darkness around the area D and B the same?
- The brightness pattern perceived is a darker stripe in region D and brighter stripe in region B, but actually the region from D to B has the same intensity.
- Ernst Mach discovered this phenomenon in 1865.
Simultaneous Contrast

- All the small squares have exactly the same intensity, but they appear to the eye progressively darker as the background becomes brighter.

- Region's perceived brightness does not depend simply on its intensity.
Human Perception Phenomena

[Diagram with four different patterns]
Simultaneous Contrast

- All the small squares have exactly the same intensity, but they appear to the eye progressively darker as the background becomes brighter.
- Region's perceived brightness does not depend simply on its intensity.
Revisiting Signals

• A **Signal** is a function that carries information
• Usually content of the signal changes over some set of spatial and/or temporal dimensions
Time-varying Signals

• Some signals vary over time: \( f(t) \)

• E.g. Audio signal

• May be thought at one level as a collection of various tones of differing audible frequencies that vary over time
Spatially-varying Signals

• Some can vary over space as well
• An image can be thought of as being a function of 2 spatial dimensions: \( f(x,y) \)
• For monochromatic images, the value of the function is the amount of light at that point \((x,y)\)
• Medical CAT and MRI scanners can produce images that are functions of 3 spatial dimensions: \( f(x,y,z) \)
Spatiotemporal Signals

• Can signals vary both spatially and temporally?
• In other word, is there such a thing as a spatio-temporal signal? Give an example?
Types of Signals

• Most naturally-occuring signals are functions having a continuous domain

• However, to store and manipulate signals in a computer, numbers are stored with finite precision

• Signals in a computer are discrete samples of the continuous domain
  – Signals manipulated by computer have discrete domains
Sampling

- Sampling: The spacing of discrete values in the domain of a signal
- Sampling rate: Number of samples taken per unit of each dimension, e.g. Samples per second, frames per second
Quantization

- Sampling: The spacing of discrete values in the range of a signal
- Usually thought of as number of bits per sample of the signal, e.g. 1 bit per pixel (b/w images), 16-bit audio, 24-bit colour images (8-bit per channel), etc.

8 levels = $2^3$; uses 3 bits to represent the value of the function
FIGURE 2.15  An example of the digital image acquisition process. (a) Energy ("illumination") source. (b) An element of a scene. (c) Imaging system. (d) Projection of the scene onto the image plane. (e) Digitized image.
Digital Images

- Computers work with discrete pieces of information
- How do we digitize a continuous image?

![Diagram showing the transition from continuous to discrete images.](image-url)
Generating a Digital Image

FIGURE 2.16 Generating a digital image: (a) Continuous image. (b) A scan line from A to B in the continuous image, used to illustrate the concepts of sampling and quantization. (c) Sampling and quantization. (d) Digital scan line.
Image Sampling & Quantization

**FIGURE 2.17** (a) Continuous image projected onto a sensor array. (b) Result of image sampling and quantization.
Digital Image Representation

- Digital image: An image $f(x,y)$ that has been digitized both in spatial coordinates and intensity values
- The value of $f$ at any point $(x,y)$ is proportional to the brightness (or gray level) of the image at that point
Digital Image Representation: Computer Model

- A digital image can be considered a matrix (or 2-D array) whose row and column indices identify a point in the image and the corresponding matrix element value identifies the gray level at that point.
Digital Image Representation: Computer Model

Pixel values in highlighted region

<table>
<thead>
<tr>
<th>98</th>
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<th>61</th>
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Samples the analog data and digitizes it.
Digital Image Representation: Computer Model

An image plotted as a function of 2 variables
Gray Level

- Light that is void of color is called monochromatic light
- The only attribute of such light is its intensity
- **Gray level**: Term generally used to describe monochromatic intensity because it ranges from black to grays and finally to white
Light-Intensity Function

- Image refers to a 2-D light-intensity function, $f(x,y)$
- The amplitude of $f$ at spatial coordinates $(x,y)$ gives the intensity (brightness) of the image at that point
- Light is a form of energy thus $f(x,y)$ must be nonzero and finite: $0 < f(x,y) < \infty$
Illumination & Reflectance

• The basic nature of $f(x,y)$ may be characterized by 2 components:
  – Illumination: The amount of source light incident on the scene being viewed, $i(x,y)$
  – Reflectance: The amount of light reflected by the objects in the scene, $r(x,y)$
Illumination & Reflectance

- \( f(x,y) = i(x,y) \cdot r(x,y) \)
- \( 0 < i(x,y) < \infty \) determined by the nature of the light source
- \( 0 < r(x,y) < 1 \) determined by the nature of the objects in a scene
Gray Level

• We call the intensity of a monochrome image $f$ at coordinate $(x,y)$ the gray level $l$ of the image at that point

• Thus, $l$ lies in the range $L_{\text{min}} \leq l \leq L_{\text{max}}$

• $L_{\text{min}}$ is positive and $L_{\text{max}}$ is finite

• Gray scale = $[L_{\text{min}}, L_{\text{max}}]$

• Common practice, shift the interval to $[0, L]$

• $0 = \text{black}, \, L = \text{white}, \, \text{values in between} = \text{gray}$
Number of Bits

- The number of gray levels typically is an integer power of 2
  \[ L = 2^k \]
- Number of bits required to store a digitized image
  \[ b = M \times N \times k \]
Resolution

- Resolution (how much you can see the detail of the image) depends on **sampling** and **gray levels**.
  - Spatial Resolution
  - Gray-level Resolution
- The **bigger** the sampling rate and the gray scale, the **better** the approximation of the digitized image from the original.
- The more the quantization scale becomes, the **bigger** the size of the digitized image.
Resolution

• Number of samples used to generate image – To our discretion
• Number of gray levels – bounded by hardware considerations
• Most common number of bits used is 8 bits, i.e. Number of gray levels = $2^8 = 256$ levels
Subsampling

**FIGURE 2.19** A 1024 × 1024, 8-bit image subsampled down to size 32 × 32 pixels. The number of allowable gray levels was kept at 256.
Subsampling Problem?

• What are some problems that may occur if your images are sampled (or subsampled) to a lower resolution?
Checkerboard Effect

- If the resolution is decreased too much, the checkerboard effect can occur.
False Contouring

- (a) Gray level = 16
- (b) Gray level = 8
- (c) Gray level = 4
- (d) Gray level = 2

- If the gray scale is not enough, the smooth area will be affected.
- False contouring can occur on the smooth area which has fine gray scales.
Nonuniformity Helps

- Nonuniform Sampling
- Nonuniform Quantization
- Can different pixels be sampled and/or quantized differently? How?
Types of Digital Images

- Binary image – 1 bit/pixel
- Grayscale image – 8 bits/pixel
- True color or RGB image – 24 bits/pixel
- Indexed image – 8 bits/pixel
Binary Images

- Efficient in terms of storage
- Document processing, handwriting, fingerprint
Grayscale Images

- The range is usually a power of 2
- 256 levels sufficient for most applications
True Color Image

- RGB image (red-green-blue)
- 16,777,216 different possible colors
Indexed Image

• The image has an associated color map, which is simply a list of all the colors used in that image
• GIF, PNG formats, etc.
Image File Size

- The number of bits (or bytes) used by an image
- **512x512 binary image**
  - \(512 \times 512 \times 1 = 262,144 \) bits = 32,768 bytes \(\approx 0.033 \) Mb
- **512x512 grayscale image**
  - \(512 \times 512 \times 1 = 262,144 \) bytes \(\approx 0.262 \) Mb
- **512x512 RGB image**
  - ??
Basic Relationships Between Pixels

- Neighbours of a pixel
- Connectivity
- Other Relationships
  - Adjacency, Path, Connected components, Region, Boundary
- Distance Measures
Neighbours of a Pixel

• A pixel $p$ at coordinate $(x,y)$ has
  – $N_4(p)$: 4-neighbours of $p$
    \[(x+1,y), (x-1,y), (x,y+1), (x,y-1)\]
  – $N_D(p)$: 4-diagonal neighbours of $p$
    \[(x+1,y+1), (x+1,y-1), (x-1,y+1), (x-1,y-1)\]
  – $N_8(p)$: 8-neighbours of $p$
    \[
    \begin{array}{ccc}
    x & x & x \\
    x & p & x \\
    x & x & x \\
    \end{array}
    
    A combination of $N_4(p)$ and $N_D(p)$
Connectivity

- Let $V$ be the set of gray-level values used to define connectivity
- **4-connectivity:**
  - 2 pixels $p$ and $q$ with values from $V$ are 4-connected if $q$ is in the set $N_4(p)$
- **8-connectivity:**
  - 2 pixels $p$ and $q$ with values from $V$ are 8-connected if $q$ is in the set $N_8(p)$
Adjacency, Path, Connected Components, Region, Boundary

- A pixel $p$ is adjacent to pixel $q$ if they are connected.
- **Path**: A sequence of distinct pixels that are adjacent to each other.
- A **connected component** set consists of a set of pixels that are adjacent to each other.
- Let $R$ be a subset of pixels in an image. $R$ is a **region** of the image if $R$ is a connected set.
- The **boundary** of the region is the set of pixels in the region that have one or more neighbours that are not in $R$. 
Distance Measures

• Let's say pixels p, q and z with coordinates \((x,y)\), \((s,t)\), \((u,v)\) respectively

• D is a distance function or metric if
  – \(D(p,q) \geq 0\), \(D(p,q) = 0\) iff \(p=q\)
  – \(D(p,q) = D(q,p)\)
  – \(D(p,z) \leq D(p,q) + D(q,z)\)
Euclidean Distance

- $D_e(p,q) = \left[ (x-s)^2 + (y-t)^2 \right]^{1/2}$
City-Block (Manhattan) Distance

- $D_4(p,q) = |x-s| + |y-t|$
- Diamond-centered at $(x,y)$
- $D_4=1$ are 4-neighbours of $(x,y)$
Chessboard Distance

- \( D_8(p,q) = \max(|x-s|, |y-t|) \)
- Square-centered at \((x,y)\)
- \( D_4=1 \) are 8-neighbours of \((x,y)\)

\[
\begin{array}{cccccc}
2 & 2 & 2 & 2 & 2 \\
2 & 1 & 1 & 1 & 2 \\
2 & 1 & 0 & 1 & 2 \\
2 & 1 & 1 & 1 & 2 \\
2 & 2 & 2 & 2 & 2 \\
\end{array}
\]

\[ D_8 = \max(D_a, D_b) \]
Next...
Recommended Readings

- Digital Image Processing (2\textsuperscript{nd} Edition), Gonzalez & Woods,
  - Chapter 2 (all)

- Matlab Tutorials
  - \textbf{Do them early} – the earlier you learn them, the more comfortable you are to work on the coming assignments
  - \textbf{Quick! Get familiar with Matlab if you have not} (using Matlab Basics 1 & 2, Matlab Primer, or any other resources that you can find)