Signals in Robot Control: Two Primary Approaches

I. Percept Inversion

\[ \text{Stimulus} = f(\text{World}) \quad \text{World} = f^{-1}(S) \]

- geometric reconstruction provides a representation for planning and deliberation
- \textit{frame} problem - completeness issues
- the functions, \( f() \), are only partially known, and are generally difficult to invert
- time spent “perceiving” often renders world models obsolete
Signals in Robot Control: Two Primary Approaches

II. Behavior Based Perception

- “the world is its own best representation”
- correlation over multi-sensor time-series feedback
- interaction - actions influence perceptions
- task-specific solutions to the frame problem
Vision - Light and Matter

• Energy from a light source is radiated uniformly over $4\pi$ steradians $\rightarrow 1/R^2$ energy distribution from a point source

• the sun delivers about 1200 Watts/m$^2$ at noon on the equator

• at optical interfaces
  
  – transmission (refraction)
  
  – reflection - diffuse or specular depending on surface properties and wavelength.
  
  – absorption - heat
  
  – heat - black body radiation

• each encounter changes the properties of light - spectral content, intensity, and polarization

...light signals carry a tremendous amount of information...
• 5th century BC - Chinese philosopher Mo-Ti created an inverted image by passing light through a pinhole into a darkened “collecting place.”

• ca. 350 BC - Aristotle viewed the eclipsing sun projected on the ground through the holes in a sieve

• 10th century - Arabian scholar Alhazen of Basra created a portable solar observatory

• 15th - notebooks of Leonardo Da Vinci

• 17th century - Johannes Kepler - “camera obscura” (Latin for “room” and “dark,” respectively)
• (1558) Giovanni Battista Della Porta “Magiae Naturalis” recommended the camera obscura as a drawing aid for artists...

• 18th century artists used the camera obscura - Jan Vermeer, Canaletto, Guardi, and Paul Sandby

• 19th century - a sheet of light sensitive paper transforms the camera obscura into the modern photographic camera.
What’s wrong with the pinhole camera?
Gathering Light

Snell’s Law

**Index of Refraction** — the ratio of the speed of light in a vacuum to that in the optical material.

\[ n = \frac{c}{v} = \sqrt{\frac{\epsilon \mu}{\epsilon_0 \mu_0}} \]

where

\( \mu \) — magnetic permeability, and
\( \epsilon \) — electric permittivity.

\[
\frac{\sin(\theta_{\text{incident}})}{\sin(\theta_{\text{transmitted}})} = \frac{n_t}{n_i},
\]
Optics - Gaussian Lens Formula

Biconvex Thin Lens

\[ \frac{1}{S_1} + \frac{1}{S_2} = \frac{1}{f} \]
Vision - Image Acquisition

...the radiant intensity function is projected onto a 2D image plane, sampled spatially, and digitized 30 times each second...
native reflexes: pupillary light reflex, Squinting, accommodation reflex - coupled verge and focus
Natural Variation

bees, fish, butterflies, birds and reptiles - are capable of seeing color, but that most mammals do not.

Herbivores - Side facing (monocular) vision systems yield almost wrap around field of view.

Carnivores - forward facing (stereo) system provides precision depth perception with a narrow field of view (< 180 degrees)

Cheetah - wide, eccentric foveal region spanning horizontal band for locating prey on the African plains.

Chamelion - turret eyes capable of both side- and forward-looking configurations

Nocturnal - reflective back surface, small birds may sacrifice muscles for size. Large animals (giant squid) may scale their eye up to 15 inches in diameter.

Fishing - some fishing birds use polarizing lens

Rattlesnake - eyes oriented to side, but forward-looking stereo pit organs (no lens) that respond selectively to IR.
Robot Vision

- Cathode Ray Tubes (CRT) -
  
  - "image dissector" - Philo Farnsworth (1927) a lens focuses image on a plate coated with cesium oxide that emits electrons when struck by light, electric and magnetic fields scan the plate sequentially (raster lines) to create a direct 1D stream of *pixels* (picture elements).
  - "iconoscope" - Vladimir Zworykin (1931)
  - "orthicon" - RCA (Albert Rose, Paul Weimer, and Harold Law, 1939)
  - "vidicon-plumbicon-saticon-pasecon-newvicon-trinicon" (1930-1980)

- Solid-State Charge-Coupled Devices (CCD) - Bell Labs (1969) a form of solid-state "bucket-brigade" for sampled analog signals that eliminates power (CRT) and corresponding signal distortions
• CMOS active pixel sensors - a photodetector and an active amplifier constructed out of three or more transistors. Arrays of active pixels constructed using complementary metal oxide semiconductor (CMOS) technology - digital cameras and image processing on a single chip.

...analogs of the human retina exist using integrated CMOS image capture chips, CMOS cameras are everywhere - cell phones and webcams. They are fast, very low power, and compact...
• $f(t) \approx$ superposition of independent signals

• *spectral* decomposition (basis for spectral filtering/Fourier transform)

• implications in *sampling*
Example: Human Voice

the open-closed resonance cavity—a constant diameter tube open at one end that radiates sound pressure into an infinitely larger environment

the open end of the cavity reflects an inverted pressure wave

\[ f(t) = \sin(2\pi F_1 t) \]
\[ f(t) = \sin(2\pi F_2 t) \]
\[ f(t) = \sin(2\pi F_3 t) \]

\[ \omega_n = (2n - 1)(c/4L) \]

several resonance modes (formants) exist simultaneously
Example: Spectral Evaluation

“...the rainbow passage...”

A screen capture from an analysis by the Computerized Speech Lab (courtesy Dr. M. Andrianopoulos): frequency content versus time; sound pressure level as a function of frequency, and amplitude versus time for a vocalization.
...a prolonged [a] vowel changes the relative placement and amplitude of the resonance modes (formants) of the vocal tract.

$F_1$ vs. $F_2$ vowel chart for 10 vowel sounds sampled from men, women, and children.
The Sampling Theorem:

*If the image contains no frequency components greater than one half the sampling frequency, then the continuous image is faithfully represented in the sampled image.*

**Aliasing:** sampling at an insufficient *rate* causes spurious information on the signal that can show up (in general) at any frequency component.
The convolution of two functions $f(x)$ and $g(x)$:
Early Processing - Convolution

The convolution of two functions $f(x)$ and $g(x)$:

\[
f(x, y) * g(x, y) = h(x, y) = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} f(u, v)g(x-u, y-v) \, du \, dv
\]

or

\[
f(x, y) * g(x, y) = h(x, y) = \sum_{-\infty}^{\infty} \sum_{-\infty}^{\infty} f(u, v)g(x-u, y-v)
\]
Early Processing - Smoothing

Low Pass Filter

$h = f \ast g$

\[ \text{sinc}(\omega) = \frac{\sin(\omega/2)}{(\omega/2)} \]

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Early Processing - Edges

Intensity Gradients

\[ \nabla g = \frac{dg}{dx} \hat{x} + \frac{dg}{dy} \hat{y} \]

\[
\frac{dg(x, y)}{dx} \approx \frac{g(x + 1, y) - g(x - 1, y)}{2}
\]

\[ \Rightarrow f_x = \begin{bmatrix} -\frac{1}{2}, & 0, & \frac{1}{2} \end{bmatrix}_{1 \times 3} \]

\[
\frac{dg(x, y)}{dy} \approx \frac{g(x, y + 1) - g(x, y - 1)}{2}
\]

\[ \Rightarrow f_y = \begin{bmatrix} -\frac{1}{2} \\ 0 \\ \frac{1}{2} \end{bmatrix}_{3 \times 1} \]
Edges - Magnitude and Direction

\[ |\nabla g| = \left[ \left( \frac{dg}{dx} \right)^2 + \left( \frac{dg}{dy} \right)^2 \right]^{\frac{1}{2}} \]

\[ = \phi = \tan^{-1}\left( \frac{dg/dy}{dg/dx} \right) \]
Edge Operators

<table>
<thead>
<tr>
<th>operator</th>
<th>$\nabla_1$</th>
<th>$\nabla_2$</th>
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<tbody>
<tr>
<td>Roberts</td>
<td>$\begin{bmatrix} 0 &amp; 1 \ -1 &amp; 0 \end{bmatrix}$</td>
<td>$\begin{bmatrix} 1 &amp; 0 \ 0 &amp; -1 \end{bmatrix}$</td>
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<tr>
<td>Prewit</td>
<td>$\begin{bmatrix} -1 &amp; 0 &amp; 1 \ -1 &amp; 0 &amp; 1 \ -1 &amp; 0 &amp; 1 \end{bmatrix}$</td>
<td>$\begin{bmatrix} 1 &amp; 1 &amp; 1 \ 0 &amp; 0 &amp; 0 \ -1 &amp; -1 &amp; -1 \end{bmatrix}$</td>
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<tr>
<td>Sobel</td>
<td>$\begin{bmatrix} -1 &amp; 0 &amp; 1 \ -2 &amp; 0 &amp; 2 \ -1 &amp; 0 &amp; 1 \end{bmatrix}$</td>
<td>$\begin{bmatrix} 1 &amp; 2 &amp; 1 \ 0 &amp; 0 &amp; 0 \ -1 &amp; -2 &amp; -1 \end{bmatrix}$</td>
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Early Processing - Edge Sharpening

Laplacian

\[ \nabla^2 g = \frac{d^2 g}{dx^2} + \frac{d^2 g}{dy^2} \Rightarrow f = \begin{bmatrix} 0 & -1 & 0 \\ -1 & 4 & -1 \\ 0 & -1 & 0 \end{bmatrix} \]