Signal Processing for Computational Imaging

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20 Greatest Engineering Achievements of the 20th Century

Selected by the U.S. National Academy of Engineering

www.greatachievements.org
20 Greatest Engineering Achievements of the 20th Century

1. Electrification
2. Automobile
3. Airplane
4. Water Supply and Distribution
5. Electronics
6. Radio and Television
7. Agricultural Mechanization
8. Computers
9. Telephone
10. Air Conditioning and Refrigeration
11. Highways
12. Spacecraft
13. Internet
14. Imaging
15. Household Appliances
16. Health Technologies
17. Petroleum and Petrochemical Technologies
18. Laser and Fiber Optics
19. Nuclear Technologies
20. High-performance Materials
Imaging

• In 1900…
  • Only simple microscopes, telescopes, and black and white photographs.

• In 2000…
  • Color photographs, movies, and television
  • New sensors that greatly expand our “vision”
    • see tiny atomic particles to vast galaxies
    • see inside the human body
    • track weather patterns, …
  • The entire microelectronics revolution is based upon imaging
Imaging = Image Formation + Processing

- Examples: optical imaging, radar imaging, computer tomography (CT), magnetic resonance imaging (MRI).
Synthetic Aperture Radar (SAR)

www.sandia.gov/RADAR
Computer Tomography (CT)

www.imaginis.com/ct-scan
Magnetic Resonance Imaging (MRI)

www.uic.edu/com/mrc/
Optical Coherence Tomography (OCT)

bil.nb.uiuc.edu
Imaging = Image Formation + Processing

Tradition scope of signal processing
Imaging is a Multidisciplinary Field
And Signal Processing is the Glue

Mathematics

Physics

Computational Imaging

Computer Science

Application domain
An Application Domain: Health Care

- In 2005, the U.S. spent 16% of its GDP on health care. It is projected that this will reach 20% by 2015.
  - Starbucks: healthcare cost exceeds coffee.
  - General Motor: healthcare cost exceeds steel.

- A quarter of total Medicare budget is spent in the last year of life; 40% of it is on the last 30 days.

Goal: Individualized treatments based on better medical imaging

- In developing countries: desire to have low-cost and effective population screening.
Hardware Approach to Imaging System Calibration

- Requires expensive hardware modification and calibration

\[ I[r] = \sum_k K[k, r] S'[k] \]
Computational Approach to Calibration

- Apply signal processing methods to form useful imagery from imperfect signal measurements.
- Use computational power to overcome physical limitations.
• Field inhomogeneity is a key factor affecting MRI image reconstruction

\[ s(k) = \int f(r) e^{-i\omega(r)t} e^{-i2\pi(k(t) \cdot r)} dr. \]

\[ s[m] = \sum_{n=0}^{N-1} a_n e^{i\phi_n m}, \]

Harmonic Retrieval!
Joint Estimation in MRI using Harmonic Retrieval Methods

Original image and field map

Standard reconstruction

Our reconstruction

H. Nguyen et al., 2007
Autofocus Problem in Synthetic Aperture Radar (SAR)

\[ g[m, n] = DFT_k^{-1}\{G[k, n]\} \]

\[ \tilde{G}[k, n] = G[k, n] e^{j\phi_e[k]} \]
MCA: MultiChannel Autofocus

\[
\hat{g}(f) = \sum_{k=0}^{M-1} f_k \varphi^{[k]}(\tilde{g}) , \quad \text{where} \quad \varphi^{[k]}(\tilde{g}) = C\{e_k\} \tilde{g}
\]

R. Morrison et al., 2007
Beyond Television... Remote Reality

M. Maitre et al., 2007
Multi-Channel Sampling

- We want to approximate the high-resolution signal \( y_0[n] \):
  \[
  f(t) \xrightarrow{\Phi_0(s)} S_h \xrightarrow{} y_0[n]
  \]

- \ldots from low-resolution signals \( \{x_i[n]\}_{i=1}^N \):
  \[
  f(t) \xrightarrow{e^{-D_1s}} \Phi_1(s) \xrightarrow{} S_{Mh} \xrightarrow{} x_1[n]
  \]
  \[
  e^{-D_2s} \xrightarrow{} \Phi_2(s) \xrightarrow{} S_{Mh} \xrightarrow{} x_2[n]
  \]
  \[
  \ldots \xrightarrow{} \ldots \xrightarrow{} \ldots
  \]
  \[
  e^{-D_Ns} \xrightarrow{} \Phi_N(s) \xrightarrow{} S_{Mh} \xrightarrow{} x_N[n]
  \]

- Challenges:
  - No assumptions on input signals.
  - Presence of fractional delays.
Minimax Design of Hybrid Filter Banks

We want to design filters \( \{F_i(z)\}_{i=1}^{N} \) to minimize the \( \mathcal{H}_\infty \) norm of the continuous-input discrete-output induced error system \( \mathcal{K} \):

\[
\|\mathcal{K}\|_\infty = \sup \frac{\|e\|_{L_2}}{\|f\|_{L_2}}
\]

\( f(t) \)
\( e^{-D_1} \)
\( \Phi_1(s) \)
\( S_h \)
\( y_0[n] \)
\( z^{-m_0} \)

\( e^{-D_{N_0}} \)
\( \Phi_N(s) \)
\( S_h \)
\( \downarrow M \)
\( \uparrow M \)
\( F_N(z) \)

\( \hat{y}_0[n] \)
\( e[n] \)

H. Nguyen and MD, 2007
Image Processing: The Key is Efficient Image Representation

- **Goal:** Parsimonious view of pictorial information

A *natural* image  
A *biological* image  
A *random* image

Natural images “live” in a very tiny bit of the space of all possible “images”
Image Representation via Transforms

**Original** domain: pixels

**Wavelet** domain: coefficients
Example of Impact on Applications
“…the 20 bits per second which, the psychologists assure us, that the human eye is capable of taking in…”

D. Gabor, 1959

One image → Human eye (≈ 5 sec.) → 100 bits

One image → JPEG-2000 (wavelets) → 1’000’000 bits
What Have We Learnt from Sputnik?

“The lesson of the past 50 years, however, is that the more humanity discovers about space, *the rarer and more precious life on Earth seems.*”

*Economists, 27 Sep 2007*
End of Part 1
Part 2
Martin Number

From ISI Web of Science: Distinct Author Summary -- Vetterli M

Top Authors:

- VETTERLI, M (88)
- DO, MN (7)
- RAMCHANDRAN, K (7)
- KOVACEVIC, J (6)
- CVETKOVIC, Z (5)
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- WIDROW, B (1)
- XIONG, ZX (1)
- YASUDA, H (1)
- ZHUANG, J (1)
Happy Birthday Martin!

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HAPPY BIRTHDAY FROM ALL OF US