Signal Transformation and Information Representation

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Introduction

Tools for Practical Source Coding
The primary focus of our work is the analysis and design of building blocks for practical compression systems. We tend to work at a level of abstraction where our parts fit in many applications, but we also sometimes follow through to final applications. To be able to influence practice, we emphasize structured signal transformations and scalar and lattice quantization. Beyond just compression, we are interested in whole communication systems, including channel coding, networking, and congestion control.

Oversampling
Though it is not obvious on the surface, the power of oversampled representations is central to the digitization that surrounds us in this digital age. For scientific processing but also for most communication and storage, acquired signals are quantized to discrete values in the process of analog-to-digital conversion (ADC). ADC is made orders of magnitude cheaper by having very coarse (e.g., one bit) discretization of a highly oversampled version of a signal; it is much cheaper to run fast than to be accurate in analog electronics. The ubiquity of these techniques in audio processing is evidenced by the obscure "1-bit DAC" imprint on CD players, yet the full power of oversampled representations for higher-dimensional signals remains to be exploited.

Nonlinearities
For reasons of both computational complexity and mathematical elegance, linear transformations are central to the theory and practice of signal processing. But there are many nonlinear operations that are not too difficult to analyze or implement that provide very valuable properties. Examples include sorting, as in the Burrows-Wheeler Transform or permutation coding; thresholding, which is prominent in denoising; and pseudolinear integer-to-integer transforms, which are promising for conventional lossy source coding and multiple description coding. We are interested in developing tools based on tractable nonlinearities.

Technology and Pedagogy
The goal in any engineering research should be to aid good engineering, specifically the design of objects and processes for the betterment of the human condition. While we strive to advance technology, at the same time we embrace the additional opportunities that come from being at an educational institution. We make some of our contribution by illuminating topics we find important to non-specialists. And we take the time to work beyond the point of having mathematical proof to also have clear, intuitive, and visual demonstrations.

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1. Signal Processing Framework for Time Resolved Computational Imaging

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Human visual experience naturally guides our imagination of what is possible when imaging with light. The image produced by a camera is a lot like what we see when we look at a scene. It is taken for granted that opaque objects completely hide what is behind them, so we cannot see around a corner; and from a visible surface, only the light directed toward the viewer can be measured.

These basic features of both human perception and all current light based imaging technology arise from the time resolution of the measurement equipment relative to the time it takes for light to traverse the scene of interest. When the measurement process is slow, the intensity of light captured is a property of the steady-state light field. When illumination varies, the transient properties of the light field enable seemingly impossible inferences of scene properties. We have developed a signal processing framework for image formation and scene understanding through impulse illumination and time-resolved imaging.

Using time-of-flight cameras and novel mathematical models for multi-path analysis of global light transport, we have demonstrated that one can infer the structure and reflectance of the hidden parts of a scene, enabling us to it look around corners.

2. Quantization of Prior Probabilities in Bayesian Group Decision-making

Sponsors
Korea Foundation for Advanced Studies
National Science Foundation Grant 0729069

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A Bayesian group decision-making model is explored. In the model, decision-makers have restricted capability that they do not know the true prior probability of each object. Instead, they can distinguish objects as one of limited number of categories. Because of this restriction, optimal quantization of prior probabilities is necessary. If the group consists of different decision-makers, i.e., decision-makers that have different cost functions, it becomes complicated to determine optimal quantization rules and decision rules. Game theory can be applied for us to understand the problems because it considers any kind of group decision-making situation. Using a Bayesian distributed detection model, we explain not only each decision-maker's optimal quantization rule to minimize mean Bayes risk error due to quantization but also its best decision rule to minimize its cost while considering others' decision-making. Especially, we consider Nash equilibria among many equilibria in game theory. We consider two cases when decision-makers are identical and when they are not identical and derive optimal quantization and decision rules. Furthermore, in the latter case, we allow the decision-makers to compete or collaborate and analyze how competition or collaboration affects the performance of quantization and decision rules. Last, we discuss the advantage of using diverse quantization rules.

3. Drift Correction for Scanning Electron Metrology

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In Scanning Electron Microscopy, drift is the differential motion of the sample being imaged with respect to the electron beam doing the imaging. Drift distortion in images generated on Scanning Electron Microscopes (SEM) poses a serious challenge for nanoscale metrology, as well as for compensation due to the time-varying properties of the drift. Most image correction methods rely on a time-independent degradation, whereas drift can differ significantly within adjacent portions of an image. A simple solution is to scan images quickly in order to minimize drift distortion, but this has the undesirable effect of producing a grainy, noisy image. Our proposed solution is an algorithm, written in MATLAB, which registers a series of rapidly scanned similar images in order to produce a low-noise drift-corrected composite.

The performance of our algorithm is assessed using simulated SEM images generated from open-source software available from NIST. Comparison of our composite images to those created by typical frame-averaging available on most SEM software yield visually stark differences. We also compare our performance against that of similar correction algorithms.

4. Optimal Quantization for Compressed Sensing

Sponsor
National Science Foundation Grant 0643836

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The idea of measuring sparse signals by random subsampling has gotten much attention from many research communities. With applications in image acquisition, sensor networks and compression, compressed sensing (CS) is now becoming more practical in nature and it becomes imperative to understand how quantization of measurements affects signal reconstruction. We utilize the field of distributed functional quantization to design optimal scalar quantizers for CS measurements. Although analytically intractable, this method can approach the best MSE performance possible using Monte Carlo integration for both fixed-rate and variable-rate quantizers. We observe a constant factor improvement in distortion compared to other practical designs. We expect similar or better improvement in the variable-rate case. Interesting extensions via the replica method are being studied.

5. Extensions of Functional Quantization

Sponsor
National Science Foundation Grant 0643836

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Functional quantization deals with the design of a quantizer that has knowledge of the computations to follow the discretization of an input signal. In recent years, there have been explorations into optimal design of a network of quantizers that can only operate locally but know a global computation that is of interest. In this sense, it is a multiple-source-single-sink architecture. We extend this theory to more general architectures such as the multiple-source-multiple-sink architecture and also the relay system. We find that the sensitivity profile, a key feature of the original functional quantization work, still holds.

6. Channels That Die

Sponsor
National Science Foundation Grants 0729069 and 0325774

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Given the possibility of communication systems failing catastrophically, we investigate limits to communicating over channels that fail at random times. These channels are finite-state semi-Markov channels. We show that communication with arbitrarily small probability of error is not possible. Making use of results in finite blocklength channel coding, we determine sequences of blocklengths that optimize transmission volume communicated at fixed maximum message error probabilities. A dynamic programming formulation is used to show that channel state feedback does not improve performance.

7. Distributed Inference Networks with Costly Wires

Sponsors
National Science Foundation Graduate Research Fellowship, Grants 0729069, 0836720, and 0801549
Siemens Corporate Research Grant: Advanced Control Methods for Complex Networked Systems

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Distributed control systems are physical constructs, incurring deployment and maintenance costs for their communication infrastructure. Inference is a central function of many distributed control systems. This research formulates and studies the tradeoff between algebraic notions of inference functionality and algebraic notions of wiring costs. It is shown that separated topology design and node placement yields optimal network design. This design problem is shown to be NP-complete, but is carried out for small network size. A natural relaxation is shown to be a reverse convex minimization problem.

8. Reconstruction of Sparse MR Images from Parallel Accelerated Data

Sponsor
National Defense Science and Engineering Graduate Fellowship
National Science Foundation Grant 0643836

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Although the technology continues to improve, Magnetic Resonance (MR) Imaging continues to be limited by the time to collect enough data to reconstruct images of sufficient diagnostic quality. To escape this bottleneck, data is acquired with multiple receiver coils simultaneously and applying techniques, such as SENSE and GRAPPA, for combining the data across these parallel coils to synthesize a complete image. Existing techniques, while theoretically sound, are greatly limited in practice by the redundancy of the coils and noise amplification. To mitigate noise amplification and extend these techniques to greater accelerate the scanning process, compressed sensing (CS) is applied to leverage the known approximate sparsity of MR images. The combination of the CS framework with parallel image reconstruction techniques like GRAPPA remains a challenging problem that we have studied, and for which we have proposed novel approaches to image reconstruction. These methods were developed and implemented using MATLAB and tested on real datasets collected at the A. A. Martinos Center for Biomedical Imaging. Initial results of this research were presented at the ISMRM Annual Meeting in Stockholm, Sweden, in May 2010.

Publications

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D. S. Weller and V. K Goyal, “Bayesian Post-Processing Methods for Jitter Mitigation in Sampling,” submitted to IEEE Trans. on Signal Processing.

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Meeting Papers, Presented

L. R. Varshney, “Communication with Unreliable Receivers,” presented at 2010 Information Theory and its Applications Workshop, La Jolla, California, February 2010.

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