Block-Based Compressed Sensing of Images and Video

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Block-Based Compressed Sensing of Images and Video

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Abstract

A number of techniques for the compressed sensing of imagery are surveyed. Various imaging media are considered, including still images, motion video, as well as multiview image sets and multiview video. A particular emphasis is placed on block-based compressed sensing due to its advantages in terms of both lightweight reconstruction complexity as well as a reduced memory burden for the random-projection measurement operator. For multiple-image scenarios, including video and multiview imagery, motion and disparity compensation is employed to exploit frame-to-frame redundancies due to object motion and parallax, resulting in residual frames which are more compressible

and thus more easily reconstructed from compressed-sensing measurements. Extensive experimental comparisons evaluate various prominent reconstruction algorithms for still-image, motion-video, and multiview scenarios in terms of both reconstruction quality as well as computational complexity.

Contents

Acronyms

BCS-SPL-DDWT block-based compressed sensing with smooth projected Landweber reconstruction using a DDWT sparsity basis. 30, 31

BCS-SPL-DWT block-based compressed sensing with smooth projected Landweber reconstruction using a whole-image DWT sparsity basis. 29–31

BCS-TV block-based compressed sensing with total-variation reconstruction. 23, 28, 30–32

BP basis pursuit. 9, 10

BPDN basis-pursuit denoising. 10, 20

CoSaMP compressive sampling matching pursuit. 10, 36

CS compressed sensing. 2, 3, 5–21, 25, 27, 29, 31, 32, 34, 36–38, 41–45, 47–51, 58–63, 69, 71, 73–83, 85–90, 92–96, 99, 102, 103, 105, 106

CT contourlet transform. 25, 26, 29

DC disparity compensation. 94–98, 101–103

DC-BCS-SPL disparity-compensated BCS-SPL. 94–99, 102

DCT discrete cosine transform. 19, 27, 29, 38, 49, 63, 64

DDWT dual-tree discrete wavelet transform. 26, 29, 38, 85, 99

DE disparity estimation. 94–99, 101–103

DISCOS distributed compressed video sensing. 61, 75, 80

DLP digital-light-processing. 14

DMD digital micromirror device. 14, 15, 22, 45, 48

DWT discrete wavelet transform. 19, 23, 25–27, 29, 32–34, 36–38, 62, 81

GOP group of pictures. 49, 50, 54–58, 60–66, 69, 85, 92

GPSR gradient projection for sparse reconstruction. 10, 27–29, 36, 38, 60, 82

IST iterative splitting and thresholding. 10

JL Johnson-Lindenstrauss. 76

k–t **FOCUSS** focal underdetermined system solver in k–t space. 61, 62, 71, 75, 76, 85, 86, 90–92

LASSO least absolute shrinkage and selection operator. 9
LDS linear dynamical system. 59
LIMAT lifting-based invertible motion adaptive transform. 62
LSQ least-squares. 78, 79

MARX model-based adaptive recovery of compressive sensing. 36, 37
MC motion compensation. 44, 50–52, 54, 58–63, 66, 69, 70, 73, 75, 76, 78, 81, 83, 85, 92, 94, 95, 97, 98, 102, 103
MC-BCS-SPL motion-compensated BCS-SPL. 50, 52–71, 75, 76, 85, 88, 90, 91, 94, 95
MCTF motion-compensated temporal filtering. 62, 63
ME motion estimation. 44, 50–52, 58–63, 66, 69, 70, 73, 75, 76, 81, 83, 85, 92, 94, 95, 97, 98, 101–103
MEMS microelectromechanical systems. 45
MH multihypothesis. 73, 78–85, 90, 92
MH-BCS-SPL multihypothesis BCS-SPL. 85, 88–92
MRI magnetic resonance imaging. 2, 58–62, 86, 89, 92
MS multiscale. 32, 86
MS-BCS-SPL multiscale, wavelet-domain block-based compressed sensing with smooth projected Landweber reconstruction. 33–35, 37–39, 41, 87, 89–91
MS-GPSR multiscale GPSR. 36, 38–41

OMP orthogonal matching pursuits. 10, 36

PAR piecewise autoregressive. 36
PL projected Landweber. 11, 24, 29
PSNR peak signal-to-noise ratio. 27–31, 38, 39, 64–69, 82, 84, 86–90, 92, 100, 101

SALSA split augmented Lagrangian shrinkage algorithm. 37–41
SAMP sparsity adaptive matching pursuits. 36
SH single-hypothesis. 73, 77, 82, 84
SpaRSA sparse reconstruction via separable approximation. 10
SPL smoothed projected Landweber. 24, 26

SRM structurally random matrix. 8, 15, 18, 20, 21, 32, 37, 38, 40–42, 87

StOMP stagewise orthogonal matching pursuit. 36

TSW-CS tree-structured wavelet compressed sensing. 36, 37, 41

TV total variation. 21, 23, 28, 30, 31, 37–42, 87–91

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Introduction

The *sampling theorem* is arguably the best known component of the theoretical foundations of the signal-processing and communications fields; its importance is paramount in that it underlies all modern signal-acquisition, sampling, sensing, and analog-to-digital conversion devices. Although introduced to the signal-processing and communications communities by Shannon in 1949 [109], the sampling theorem can be traced to earlier work by telegraphers and mathematicians (see, e.g., [82]). In essence, the sampling theorem states that, if a signal contains no frequencies higher than bandlimit W, then it can be perfectly reconstructed from samples acquired at a rate of at least $2W$. This latter quantity, commonly known as the *Nyquist rate*, thus represents the slowest rate at which sampling of any bandlimited signal can be acquired and still permit perfect reconstruction.

However, this traditional sampling theory is founded on relatively minimal prior knowledge on the signal being sampled — i.e., its bandlimit W. While traditional sampling theory has the advantage of applying to *any* signal satisfying this bandlimit constraint, we are commonly interested in more restricted classes of signals, i.e., those that are known to possess much more structure, and thus fewer degrees of freedom, than dictated by the signal bandlimit [8]. A well-known example is that of bandpass signals in which the signal is present over only a limited band of frequencies — under such bandpass structure, bandpass sampling (e.g., [129]) can acquire the signal with a sampling rate slower than $2W$. More recent literature has witnessed an explosion of interest in sensing that exploits structured prior knowledge in the general form of *sparsity*, meaning that signals can be represented by only a few coefficients in some transform basis. Like bandpass sampling, exploitation of such sparse structure within signals can effectively permit sampling at rates well below $2W$.

Central to much of this recent work is the paradigm of compressed sensing (CS)[1] (e.g., [18, 22, 38]) which permits relatively few measurements of the signal to be acquired in a linear fashion while still permitting exact reconstruction via a relatively complex and nonlinear recovery process. While much CS literature is rather generic in that it is not tied to any specific class of signal beyond a general assumption of sparsity, there has been significant interest in CS specifically tailored to imaging applications. Indeed, recent work in the CS field has seen proposals for not only sensor devices but also reconstruction algorithms designed specifically for a variety of imagery signals.

The goal of this monograph is to overview some of these methods. A primary focus is an examination of the state of the art in CS reconstruction for various imaging modalities, including still images, motion video, and multiview imagery. Throughout, we focus on photographic imagery which is acquired in the spatial domain of the image, a paradigm which is ubiquitous throughout image-processing applications. This stands in contrast to a significant portion of existing CS literature that has targeted, with substantial success, specific medical-imaging applications — in particular, magnetic resonance imaging (MRI), which is acquired directly in a Fourier-transform space. The potential for CS to significantly expedite MRI acquisition is relatively well established and already well covered tutorially in the literature (e.g., [83, 84]). On the other hand, CS for photographic imagery

[1] Also known as *compressive sampling* or *compressive sensing.*

acquired in the spatial domain is a comparatively emerging area and, thus, the topic of the present monograph.

An additional focus of this monograph is on CS reconstruction as applied on image blocks. In such block-based compressed sensing (BCS), an image is partitioned into small non-overlapping blocks which are acquired independently but reconstructed jointly. BCS is motivated primarily for reasons of reduced computational complexity and memory burdens. These can become impractically large for the CS of images and video as a result of the increased dimensionality (i.e., 2D and 3D) of such signals.

We note also that our discussion is not intended to serve as an in-depth tutorial on the theory or mathematics of CS; rather, there exist several excellent overviews on this subject (e.g., [7, 20, 22]). Instead, our coverage of CS theory here will be brief, while the specifics of the application of BCS to natural imagery will consume the bulk of the discussion.

The remainder of the monograph is organized as follows. Section 2 briefly overviews CS theory, including acquisition and reconstruction processes. Section 3 then considers the CS of a single still image, focusing on a variety of techniques to reconstruct such images from random CS measurements. Section 4 extends these concepts to the CS of video with an emphasis on reconstruction from motion-compensated residuals, and then Section 5 adds multihypothesis prediction to such motion-based CS reconstruction. Section 6 finally considers the CS of multiview images and video in which a scene is imaged from several viewpoints simultaneously. We end the monograph by making several concluding remarks.

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