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研究課題名（和文）圧縮センシングとスパース表現の実時間処理技術の研究

研究課題名（英文）Research on real-time processing of compressive sensing and sparse representation

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研究成果の概要（和文）：圧縮センシングとスパース表現ための辞書学習について新しい技術とアルゴリズムを研究した。p－ノルムやLogタイプ、行列式タイプなどの新しいスパース尺度を提案し、それらを拘束条件として導入し問題の公式化を作り出し、そしてそれらを効率的解ける新しい方法とアルゴリズムを出来上がった。シミュレーションと実環境での実験でその有効性を確認した。さらに、これら新しい方法の実の応用を行った。その1つとしては、Wi-Fiなとの無線電波環境でDevice-free者の探査と精密に位置の特定ができるということであった。また、画像ののノイズ除去とビデオのキーフレームの構成などの応用もできることを確認した。

研究成果の学術的意義や社会的意義
１）次世代移動通信は圧縮センシングが非常に重要な技術という位置付けがあるが、そのデバイス化ための効率的と実時間的処理が必要であり、いま、１つボトルネックとなっている。我々の研究はこれを解決するに向かて研究の重要なステップを踏んだ。

２）Wi-Fiなとの無線電波環境でDevice-free者の探査と精密に位置の特定ができるということは重要な応用ができる。例えば、建物のなくWi－ふぃなどの無線源があれば、なの装置も待たない侵入者を探査と精密的位置を特定ができる。また、画像ののノイズ除去とビデオのキーフレームの構成などについても重要な応用ができる。

研究成果の概要（英文）：We researched on the compressive sensing and the dictionary learning for sparse representation of signal/image. We proposed several new measure for sparsity, such as p-norm, log-type measure, Det-type measure, etc. Then we use these measures to formulate compressive sensing and sparse representation problem. We further worked out effective methods and algorithms for solving these problems. Simulations and practical experiments showed the effectiveness. We also applied the methods to some practical engineering tasks. E.g., to detect and to accurately determine the position of persons in the environment with wireless communication wave such as Wi-fi. They can also be sued for denoising of signal or image and, key-frame construction of video, etc.

研究分野：人工知能、機械学習

キーワード：スパース表現　圧縮センシング　辞書学習　確率的情報処理　実時間処理

様　式　C－１９、F－１９－１、Z－１９、CK－１９（共通）

１．研究開始当初の背景

Sparse Representations (SR) and compressive sensing (CS) of signals have received a great deal of attentions in recent years. The big success of invoking "sparsity" is essentially due to the fact that most natural signals can be represented by a linear combination of a small number of elementary components, called atoms, which are chosen from an overcomplete dictionary (the number of atoms is greater than the dimension of the signal). They have applications, or potential applications, such as, denoising, compression, inpainting, super resolution, blind source separation (BSS), communication, linear regression, variable selection, etc. A key problem related to SR and CS is the choice of the dictionary employed to decompose the signals of interest in an efficient manner. A simple approach is to consider predefined dictionaries, such as the Discrete Cosine Transform (DCT) and wavelets. Another approach is to use an adaptive dictionary, which is learned from the signals that need to be represented, thereby obtaining better matches to the contents of the signals. The learned dictionary has the potential for offering better performance compared with that obtained by predefined dictionaries. In the static data setting, batch processing for SR and CS have been widely used in, for example, image processing tasks, where an overcomplete dictionary is adapted using all the training data simultaneously and is trained for the corrupted image, forcing each patch in the image to have a sparse representation describing its content.

２．研究の目的

Real-time sparse representation (SR) and real-time compressive sensing (CS) processing of time sequential data, such as video, audio, etc., is an important but still a bottleneck for realistic applications. They are so important that without them SR and CS cannot be really used in the practice. But it is a very challenging topic because there is still no processing scheme for such a process. The algorithm must work with updating style associated with sample to sample as a time sequence. It is required to converge so fast that can follow the environment varying in most realistic situations. The calculation must be simple enough to be embedded in realizable chips. Therefore this research includes a real-time SR and CS scheme, online dictionary learning algorithm and online sparse coding, or online CS algorithm. Then resultant method will be applied for communication with CS of real-time signal, real-time video denoising, inpainting, real-time audio noise or echo cancellation, single-pixel video camera and 3D super-resolution microcopy and its automatic processing.

３．研究の方法

Our research focuses on real-time sparse representation and compressive sensing for dynamic datasets as time sequences. First, we will develop a real-time processing scheme for SR and CS, which can handle samples or sample blocks of signals sequentially. Second, we develop algorithms for sparse coding, or CS, and dictionary learning that can work both in batch and real-time style, and evaluated them theoretically and experimentally. Third, we combine these algorithms into the mentioned real-time processing scheme above. As applications of resultant methods, we develop new technologies, such as communication with CS of real-time signal, real-time video denoising, inpainting, real-time audio noise or echo cancellation, single-pixel video camera, 3D super-resolution microcopy and its automatic processing, etc., which can be applicable in the practice.

４．研究成果

研究成果の概要：圧縮センシングとスパース表現ための辞書学習について新しい技術とアルゴリズムを研究した。p－ノルムや Log タイプ、行列式タイプなどの新しいスパース尺度を提案し、それらを拘束条件として導入し問題の公式化を作り出し、そしてそれらを効率的解ける新しい方法とアルゴリズムを出来上がった。シミュレーションと実環境での実験でその有効性を確認した。さらに、これら新しい方法の実の応用を行った。その１つとしては、Wi-Fi などとの無線電波環境で Device-free 者の探査と精密に位置の特定ができるということであった。また、画像ののノイズ除去とビデオのキーフレームの構成などの応用もできることを確認した。詳細は下記の通りである。

(1) An Accurate and Robust Approach of Device-Free Localization with Convolutional Autoencoder

Device-free localization (DFL), as an emerging technology that locates targets without any attached devices via wireless sensor networks, has spawned extensive applications in the Internet of Things (IoT) field. For DFL, a key problem is how to extract significant features to characterize raw signals with different patterns associated with different locations. To address this problem, in this paper, the DFL problem is formulated as an

image classification problem. Moreover, we design a three-layer convolutional autoencoder (CAE) neural network to perform unsupervised feature extraction from raw signals followed by supervised fine-tuning for classification. The CAE combines the advantages of a convolutional neural network (CNN) and a deep autoencoder (AE) in the feature learning and signals reconstruction, which is expected to achieve good performance for DFL.
Publication: Lingjun Zhao, Huakun Huang, Xiang Li, Shuxue Ding*, Haoli Zhao, and Zhaoyang Han, An Accurate and Robust Approach of Device-Free Localization with Convolutional Autoencoder, accepted by IEEE Internet of Things Journal (Mar. 2019).

2) Lp Norm Independently Interpretable Regularization based Sparse Coding for Highly Correlated Data
Sparse coding, which aims at finding appropriate sparse representations of data with an overcomplete dictionary set, is a well-established signal processing methodology and has good efficiency in various areas. Varying sparse constraint can influence performances of sparse coding algorithms greatly. However, commonly used sparse regularization may be not robust in high coherence condition. In this paper, inspired from Independently Interpretable Lasso (IILasso), which considers coherence of sensing matrix columns in constraint to implement the strategy of selecting uncorrelated variables, we propose a new regularization by introducing lp norm ($0 < p < 1$) into the regularization part of IILasso. The new regularization can efficiently enhance performances in obtaining sparse and accurate coefficient. To solve the optimization problem with the new regularization, we propose to use the coordinate descent algorithm with weighted l1 norm, named Independently Interpretable Weighted Lasso (IIWLasso), and the proximal operator, named Independently Interpretable Iterative Shrinkage Thresholding Algorithm (II-ISTA) and Independently Interpretable Proximal Operator for l2/3 norm regularization (II2/3PO).
Publication: Haoli Zhao, Shuxue Ding*, Xiang Li, and Huakun Huang, Lp-Norm Independently Interpretable Regularization based Sparse Coding for Highly Correlated Data, IEEE Access, Vol. 7, No. 1, pp. 53542-53554 (May. 2019).

3) Improved Sparse Coding Algorithm with Device-Free Localization Technique for Intrusion Detection and Monitoring
Device-free localization (DFL) locates target in a wireless sensors network (WSN) without equipping with wireless devices or tags, which is an emerging technology in the fields of intrusion detection and monitoring. In order to achieve an accurate result of DFL, the conventional works adopt l1 norm as a regularizer to take the full potential of sparsity for locating targets. Contrasting to the previous works, we exploit the l2,1 norm as the regularizer and devise an efficient optimization method with a proximal operator-based scheme, which leads the proposed improved-sparse-coding algorithm with proximal operator (ISCPO). Compared with the state-of-the-art methods that adopt l1 norm as the regularizer, the proposed algorithm can improve the joint sparsity of sparse solution.
Publication: Huakun Huang, Zhaoyang Han, Shuxue Ding, Chunhua Su* and Lingjun Zhao, Improved Sparse Coding Algorithm with Device-Free Localization Technique for Intrusion Detection and Monitoring, Symmetry 2019, 11, 637; doi:10.3390/sym11050637 (May. 2019).

4) Intrusion Detection Based on Device-Free Localization in the Era of IoT
Device-free localization (DFL) locates targets without being equipped with the attached devices, which is of great significance for intrusion detection or monitoring in the era of the Internet-of-Things (IoT). Aiming at solving the problems of low accuracy and low robustness in DFL approaches, in this paper, we first treat the RSS signal as an RSS-image matrix and conduct a process of eliminating the background to dig out the variation component with distinguished features. Then, we make use of these feature-rich images by formulating DFL as an image classification problem. Furthermore, a deep convolutional neural network (CNN) is designed to extract features automatically for classification. The localization performance of the proposed background elimination-based CNN (BE-CNN) scheme is validated with a real-world dataset of outdoor DFL. In addition, we also validate the robust performance of the proposal by conducting numerical experiments with different levels of noise.
Publication: Lingjun Zhao, Chunhua Su, Huakun Huang, Shuxue Ding*, Zhaoyang Han, Xiang Li, Intrusion Detection based on Device-Free Localization in the Era of IoT, Symmetry 2019, 11, 630; doi:10.3390/sym11050630 (May 2019).

5) Total Variation Denoising with Non-convex Regularizers
Total variation (TV) denoising has attracted considerable attention in 1-D and 2-D signal processing. For image denoising, the convex cost function can be viewed as the regularized linear least squares problem (l1 regularizer for anisotropic case and l2 regularizer for isotropic case). However, these convex regularizers often underestimate the high-amplitude components of the true image. In this paper, non-convex regularizers for 2-D TV denoising models are proposed. These regularizers are based on the Moreau envelope and minimax-concave penalty, which can maintain the convexity of the cost functions. Then, efficient algorithms based on forward-backward splitting are proposed to solve the new cost functions. The numerical results show the effectiveness of the proposed non-convex regularizers for both synthetic and real-world image.
Publication: Jian Zou, Marui Shen, Haifeng Li, Guoqi Liu, and Shuxue Ding*, Total Variation Denoising with Non-convex Regularizers, IEEE Access, Vol. 7, No. 1, pp. 4422-4431 (Jan. 2019).

6) Deep Neural Network Structured Sparse Coding for Online Processing
Sparse coding, which aims at finding appropriate sparse representations of data with an overcomplete dictionary set, has become a mature class of methods with good efficiency in various areas, but it faces limitations in immediate processing such as real-time video denoising. Unsupervised deep neural network structured sparse coding (DNN-SC) algorithms can enhance the efficiency of iterative sparse coding algorithms to achieve the goal. In this paper, we first propose a sparse coding algorithm by adding the idea ``weighted" in the iterative shrinkage thresholding algorithm (ISTA), named WISTA, which can enjoy the benefit of the lp norm ($0 < p < 1$) sparsity constraint. Then, we propose two novel DNN-SC algorithms by combining deep learning with WISTA and the iterative half thresholding algorithm (IHTA), which is the l0:5 norm sparse coding algorithm.
Publication: Haoli Zhao, Shuxue Ding*, Xiang Li, and Huakun Huang, Deep Neural Network Structured Sparse Coding for Online Processing, IEEE Access, Vol. 6, No. 1, pp. 74778-74791 (Dec. 2018).

7) Nonnegative Sparse Representation of Signals with a Determinant-Type Sparsity Measure Based on the DC Programming
Nonnegative sparse representation has become highly popular in certain applications in the context of signals and corresponding dictionaries that have nonnegative limitations. Applying an adaptive dictionary for sparse representation of nonnegative signals has been shown to be very effective; but constructing adaptive dictionary, i.e., dictionary learning, remains a challenge. In this paper, we attempt to design an effective and tailored algorithm for the sparse representation of nonnegative signals. We consider the so-called determinant sparsity measure formed with the determinant of the Gram matrix of sparse coefficients. Based on the determinant measure, we formulate the nonnegative dictionary learning problem that is optimization of a non-convex function. For reducing the computational complexity of the optimization, the difference of convex functions (DC) programming is employed since the non-convex function can be set to the form of difference of two convex functions.
Publication: Benying Tan, Shuxue Ding*, Yujie Li, and Xiang Li, Nonnegative Sparse Representation of Signals with a Determinant-Type Sparsity Measure Based on the DC Programming, IEEE Access, Vol. 6, No. 1, pp. 67301-67315 (Nov. 2018)

8) An Accurate and Efficient Device-Free Localization Approach Based on Sparse Coding in Subspace
In practical device-free localization (DFL) applications, for enlarging the monitoring area and improving localization accuracy, too many nodes need to be deployed, which results in a large volume of DFL data with high dimensions. This arises a key problem of seeking an accurate and efficient approach for DFL. In order to address this problem, this paper regards DFL as a problem of sparse-representation based classification; builds a sparse model; and then proposes two sparse-coding-based algorithms. The first algorithm, sparse coding via the iterative shrinkage-thresholding algorithm (SC-ISTA), is efficient for handling high-dimensional data. And then, subspace techniques are further utilized, followed by performing sparse coding in the low-dimensional signal subspace, which leads to the second algorithm termed subspace-based SC-ISTA (SSC-ISTA).
Publication: Huakun Huang, Haoli Zhao, Xiang Li, Huawei Huang, Shuxue Ding*, Zhenni Li, and Lingjun Zhao, An Accurate and Efficient Device-Free Localization Approach Based on Sparse Coding in Subspace, IEEE Access, Vol. 6, No. 1, pp. 61782-61799 (Oct. 2018)

9) Accurate Defect Detection in Thin-Wall Structures with Transducer Networks via Outlier Elimination

For the sake of structural health monitoring for defect detection in thin-wall structures, we present an outlier analysis approach by using robust principal component analysis (Robust PCA) for the Lamb wave signals generated by a transducer network. The signal matrix is decomposed into a low-rank matrix and a sparse matrix that contains outliers. By presenting a rank approximation function that matches the true rank more closely than does the nuclear norm and comparing a set of non-convex penalty functions to approximate the l0-norm, we derive an approximated non-convex Robust PCA (ANC-RPCA) algorithm to identify and even eliminate outliers in the data. This algorithm is able to find efficient defect detection methods under dimension-reduction conditions for high-dimensional measurement signals. The elimination of outliers is also evaluated by introducing the statistical Wasserstein distance, which provides a representation of the statistical distribution of the data.

Publication: Xiang Li, Shuxue Ding, and Benying Tan, Accurate Defect Detection in Thin-Wall Structures with Transducer Networks via Outlier Elimination, IEEE Sensors Journal, Vol. 18, No. 23, pp. 9619-9628 (Dec. 2018).

10) Manifold Optimization-based Analysis Dictionary Learning with an L1/2-norm Regularizer Learning Systems

Recently there has been increasing attention towards analysis dictionary learning. In analysis dictionary learning, it is an open problem to obtain the strong sparsity-promoting solutions efficiently while simultaneously avoiding the trivial solutions of the dictionary. In this paper, to obtain the strong sparsity-promoting solutions, we employ the ℓ1/2 norm as a regularizer. The very recent study on ℓ1/2 norm regularization theory in compressive sensing shows that its solutions can give sparser results than using the ℓ1 norm. We transform a complex nonconvex optimization into a number of one-dimensional minimization problems. Then the closed-form solutions can be obtained efficiently. To avoid trivial solutions, we apply manifold optimization to update the dictionary directly on the manifold satisfying the orthonormality constraint, so that the dictionary can avoid the trivial solutions well while simultaneously capturing the intrinsic properties of the dictionary.

Publication: Zhenni Li, Shuxue Ding, Yujie Li, Zuyuan Yang, Shengli Xie, Wuhui Chen, Manifold Optimization-based Analysis Dictionary Learning with an L1/2-norm Regularizer Learning Systems, Neural Networks (SCI), Vol. 98, No. 2. pp. 212-222 (Feb. 2018).

５．主な発表論文等

〔雑誌論文〕（計 10 件）

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⑥ Deep Neural Network Structured Sparse Coding for Online Processing, Haoli Zhao, Shuxue Ding, Xiang Li, and Huakun Huang, Deep Neural Network Structured Sparse Coding for Online Processing, IEEE Access, Vol. 6, No. 1, pp. 74778-74791 (Dec. 2018).

⑦ Nonnegative Sparse Representation of Signals with a Determinant-Type Sparsity Measure

Based on the DC Programming, Benying Tan, Shuxue Ding, Yujie Li, and Xiang Li, Nonnegative Sparse Representation of Signals with a Determinant-Type Sparsity Measure Based on the DC Programming, IEEE Access, Vol. 6, No. 1, pp. 67301-67315 (Nov. 2018)
⑧ An Accurate and Efficient Device-Free Localization Approach Based on Sparse Coding in Subspace, Huakun Huang, Haoli Zhao, Xiang Li, Huawei Huang, Shuxue Ding, Zhenni Li, and Lingjun Zhao, An Accurate and Efficient Device-Free Localization Approach Based on Sparse Coding in Subspace, IEEE Access, Vol. 6, No. 1, pp. 61782-61799 (Oct. 2018)
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⑩ Manifold Optimization-based Analysis Dictionary Learning with an L1/2-norm Regularizer Learning Systems, Zhenni Li, Shuxue Ding, Yujie Li, Zuyuan Yang, Shengli Xie, Wuhui Chen, Manifold Optimization-based Analysis Dictionary Learning with an L1/2-norm Regularizer Learning Systems, Neural Networks (SCI), Vol. 98, No. 2. pp. 212-222 (Feb. 2018).

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⑤ Haoli Zhao, Shuxue Ding, Yujie Li, Zhenni Li, Xiang Li and Benying Tan, Dictionary Learning for sparse representation using weighted l1-norm, Proc. 2016 IEEE Global Conference on Signal and Information Processing (GSIP 2016, Greater Washington, D.C., USA, December 7-9, 2016), pp. 292-296.

〔図書〕（計 0 件）

〔産業財産権〕
○出願状況（計 0 件）

○取得状況（計 0 件）

〔その他〕
ホームページ等

６．研究組織

(1)研究分担者

(2)研究協力者