様　式　Ｃ－１９、Ｆ－１９－１、Ｚ－１９　（共通）

科学研究費助成事業　　研究成果報告書

令和　２ 年　 ６ 月 ２１ 日現在

機関番号：８２４０１
研究種目：基盤研究(C)（一般）
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研究課題名（和文）High-Order Deep Learning Models: Theoretical Study and Applications

研究課題名（英文）High-Order Deep Learning Models: Theoretical Study and Applications

研究代表者
ＺＨＡＯ　ＱＩＢＩＮ（Zhao, Qibin）

国立研究開発法人理化学研究所・革新知能統合研究センター・ユニットリーダー

研究者番号：３０５９９６１８

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研究成果の概要（和文）：テンソル分解やテンソルネットワーク（TN）は、近年、機械学習やデータマイニング、コンピュータビジョンの分野で注目度が高まっている。しかし、未解決の問題が多く、機械学習への影響が限定されています。本プロジェクトでは、テンソルネットワークの基本的なモデルと理論を研究し、データ表現やモデル表現への応用を行った。大規模データ補完や画像デノイジングに適用可能な高速かつスケーラブルなアルゴリズムとともに、新規なテンソル分解モデルを導入した。また、テンソルネットワーク表現に基づくディープマルチタスク、マルチモデル学習、マルチGANs法を開発し、強力な表現力と経済的なモデル複雑性を示している。

研究成果の学術的意義や社会的意義
Tensor representation and tensor networks have shown to be useful in deep learning models. This project has further promoted to solve the challenging problems in deep learning methods by using TN technology.

研究成果の概要（英文）：Tensor decomposition and tensor networks (TNs) have recently gained increasing attentions in machine learning, data mining and computer vision fields due to its effectiveness in efficient computation and model compression in deep learning. However, there are many open problems that are still unexplored, which limits its impact in machine learning. In this project, we studied the fundamental model and theory of tensor networks and applied it for data representation and model representation. We have introduced a novel tensor decomposition model together with fast and scalable algorithms which can be applied to large-scale data completion and image denoising. In addition, we also developed deep multi-task, multi-model learning and multiple GANs methods based on tensor network representations, which shows powerful expressive ability and economic model complexity.

研究分野：Information Science

キーワード：Tensor decomposition　Tensor networks　Multi-modal learning　Tensor completion

１．研究開始当初の背景

(1) Tensors (multiway arrays) provide a faithful and efficient way to represent the multidimensional structured data. Tensor decomposition enable us to explicitly take the structure dependency within data into account and effectively capture the underlying multiple sets of latent factors. Thus, its theory and algorithms have been an active area of study within the past decade.

(2) Deep learning techniques have gained the considerable attention in both academic and industry fields due to its significant performance in real-world applications. However, there are some major limitations of deep learning techniques such as the high computational complexity and huge number of parameters. In addition, many hyperparameters need to be tuned such as the number of layers, number of hidden units, learning rate, etc.

(3) Tensor networks (TNs) have recently gained increasing attentions in machine learning, data mining and computer vision fields due to its effectiveness in efficient computation and model compression in deep learning. However, there are many open problems that are still unexplored, which limits its impact in machine learning.

２．研究の目的

(1) This project aims to investigate several novel machine learning frameworks. To establish a high-order deep learning framework by exploiting tensor modeling of input, output and weight parameters. To establish a deep tensor decomposition framework, leading to the powerful nonlinear tensor latent representations. To apply tensor models for some real-world applications.

(2) This study also aims to understand the principle of TN by investigating the fundamental theory of TN, and to develop scalable and efficient learning algorithms for TN that can be applied to large-scale data analysis and machine learning applications. Based on these fundamental theory and algorithm studies, TN applied to deep convolutional neural network (CNN), multi-task, multi-view, and multi-modal learning can be further studied and improved with theoretical support. Moreover, this project will further explore how to use TN technology to solve more challenging problems in machine learning, which has not studied yet.

３．研究の方法

(1) We study the fundamental model and algorithm of tensor decomposition and tensor networks. Specifically, we study tensor ring decomposition model and theory. The expressive power will be analyzed systematically, and rank property, basic principle of arithmetic is studied. Then, these theories will be further discussed and extended to general TNs. To learn the TN representation of large-scale data, the scalable and fast algorithms will be developed. For specific algorithms, the popular regularizations such as non-negative, sparsity, smoothness are employed to handle various situations.

(2) We study the tensor methods for representing data, such as data completion problem, image denoising, super-resolution problem of hyperspectral image. For different applications, we developed fast and scalable tensor network-based machine learning algorithms.

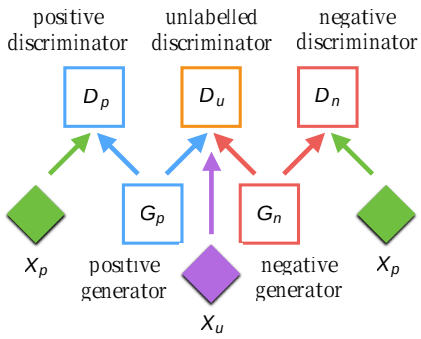
(3) We study tensor networks for the representation of model parameters. Specifically, we show how to use

tensor networks to deep neural network models, which is useful for model compression, efficient computation, knowledge sharing in multi-task learning, and powerful feature fusion strategy in multi-modal learning.

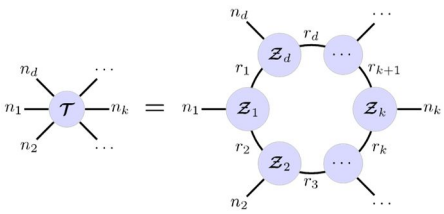
4．研究成果

(1) We have studied the tensor based deep learning model and algorithms. In the traditional deep learning methods, each layer is considered as a vector and the connection between layers is considered as a matrix. However, the real-world data is usually represented as a high order tensor. To this end, we formulate the deep learning framework by considering each layer as a tensor and the connection between the layers as multilinear operations based on multiple matrices. The proposed model is able to capture the structural information of data and to significantly reduce the number of model parameters, which shows better performance on high-dimensional data classification tasks.

(2) We have developed a new tensor based generative adversarial network, which use tensors as input and output, the fully connected layer can be modeled by multilinear product on each tensor mode. The experimental results show that our method can alleviate the mode collapse problem of GAN. In addition, we have proposed the framework of learning multiple GANs to solve the positive unlabeled learning problem. The objective is to learn two generators simultaneously by three discriminators (see the right figure). Each generator can capture one class distribution. The newly developed PU learning algorithm can greatly reduce the required number of labelled training samples without significantly decreasing the performance.



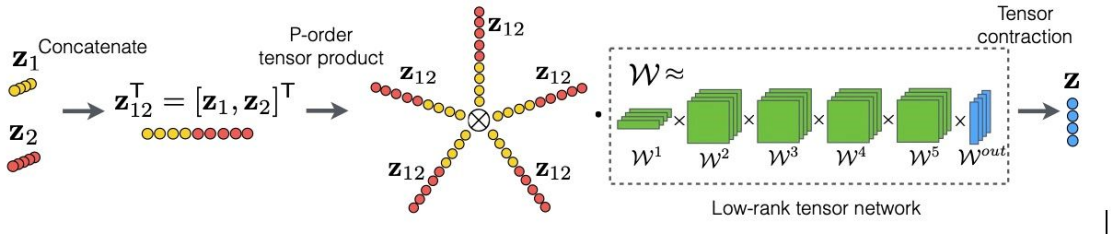
(3) We have introduced a new type of tensor decomposition model, which is called tensor ring decomposition (see the right figure). We studied the theoretical ground and the mathematical properties of the proposed model. Then, we developed several algorithms to solve this model. Finally, we applied it to represent the fully connected weight parameters, yielding a significant compression for model complexity. The proposed tensor ring model has already been well-known in tensor community and been applied to many deep learning models by world-wide researchers.



(4) We have proposed a robust tensor decomposition approach for tensor completion by defining a new tubal nuclear norm on tensors. The tubal nuclear norm has orientation invariant property which is the key contribution to improve the robustness and performance for tensor completion task. The theory analysis of tensor recovery condition is the main contribution in this work.

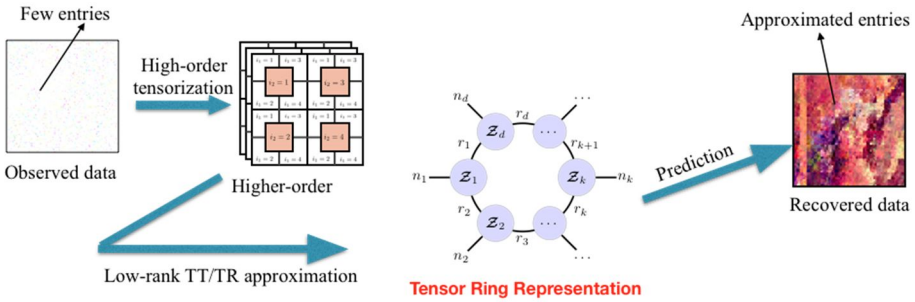
(5) We have developed a deep multimodal learning architecture based on multilinear tensor fusion of latent layers. The proposed tensor fusion strategy is able to capture high-order interactions for inter-modal and intra-modal features, which has more expressive power. In addition, we apply tensor network to represent

weight parameters, which thus reduce the computation complexity dramatically (see figure below). The proposed method can improve the performance while not increasing model and computation complexity.

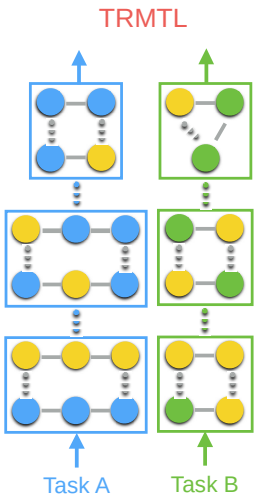


(6) We have studied the theory analysis of matrix completion under linear transformations. This work provides rigorous theory support for many "non-local" based low-rank completion methods. In addition, the proposed framework is able to improve matrix completion performance by low-rankness under the multiple transformations. Experiments results show its advantages in image in-painting task.

(7) We have developed several tensor completion algorithms based on tensor ring model. By defining tensor ring based nuclear norm, we can solve low-rank tensor approximation by nuclear norm optimizations. For large-scale data, we have developed an efficient randomized tensor ring decomposition algorithm, which is fast and scalable to very large tensors. The experiments on image completion, hyperspectral image completion and denoising demonstrate that our method can obtain state-of-the-art performance under highly missing rate, and scalable to very large data (see figure below).

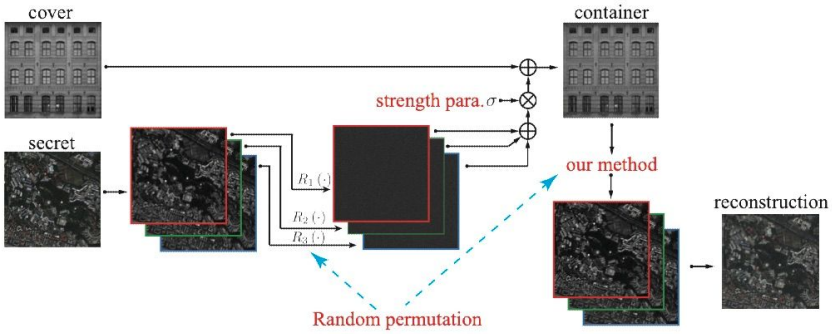


(8) We have studied multi-task deep learning models by using high-order tensor network technology. The existing multi-task deep learning models mostly based on sharing the lower layers and having individual upper layers for each task. The problem is that such framework cannot handle the case when different tasks have different input dimensions and when different tasks have heterogenous network architecture. To solve this challenging problem, we proposed a new framework, which allows us to use heterogenous network architecture for individual tasks, by leveraging tensor ring representation of weight parameters of each layer and some of latent core tensors sharing between tasks (see the right figure). The experiments demonstrated that our method is more flexible with high performance.



(9) We have proposed a new type of tensor decomposition to find the latent low-rank tensors under reshuffling operations. The proposed method is based on convex tensor decomposition. As compared to

existing convex tensor decompositions which often require each component to be low-rank on each mode, our method relax the low-rankness along specific mode unfolding to the low-rankness under random reshuffling operations. As a result, our method can theoretically guarantee the exact recovery of true latent components. Moreover, this property allows us to apply it to a novel application of image steganography (see figure below).



(10) We have developed several novel methods for epilepsy focal detection based on iEEG data. Since iEEG data with well-labelled annotations by clinical experts is very difficult to obtain, we proposed to use PU learning, one-dimensional CNN, and data augmentation methods to improve the performance of epilepsy focal detection based on iEEG. The research is quite practical for hospital to provide an AI based intelligent assistive diagnosis system.

５．主な発表論文等

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３．雑誌名 Machine Learning	６．最初と最後の頁 603～622
掲載論文のDOI（デジタルオブジェクト識別子） 10.1007/s10994-019-05846-7	査読の有無 有
オープンアクセス オープンアクセスではない、又はオープンアクセスが困難	国際共著 －

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〔図書〕　計0件

〔産業財産権〕

〔その他〕

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６．研究組織

	氏名 （ローマ字氏名） （研究者番号）	所属研究機関・部局・職 （機関番号）	備考
研究分担者	曹　建庭 (Cao Jianting) (20306989)	埼玉工業大学・工学部・教授 (32410)	