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研究課題名（和文）Data-driven Filter Design and Implementation for Snapshot Hyperspectral Imaging

研究課題名（英文）Data-driven Filter Design and Implementation for Snapshot Hyperspectral Imaging

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研究成果の概要（和文）：本研究プロジェクトは、スペクトル再構成の精度を向上させるため、カメラの感度曲線の最適化を工夫してきました。具体的には、RGB画像からスペクトル画像の復元に対して、カメラの感度曲線の影響を調べました。更に、再構成の精度を改善するため、既存のカメラデータベースから最適なカメラ感度曲線の選ぶ方法を提案しました。また、製造条件を考えた上、最適なカメラ感度曲線を自由に設計することも成功しました。ハイブリッド融合方式の場合、カメラ感度曲線の最適化も先駆的に展開しました。更に、スペクトルの再構成ではなく、シーン認識に対して、カメラ感度曲線の役割と最適化の効果も解明しました。

研究成果の学術的意義や社会的意義
深層学習を用いてイメージングハードウェアの最適化はとても挑戦的な研究課題です。本研究では、カメラの感度曲線の最適化方法を開発する上、スペクトル再構成の精度を向上させた。更に、製造上の拘束も考慮したので、アルゴリズムによる設計結果はフィルターで忠実に実装が可能であることも示した。

研究成果の概要（英文）： The research purpose of this project is to find the best spectral response functions for accurate multispectral-to-hyperspectral reconstruction using deep neural networks, and when necessary, implement the deeply learned filters by using film manufacturing technologies. We have tried to indentify the best camera spectral response curves from a given camera database, and design the optimal IR-cut filter for RGB-based spectral reconstruction. We have also examined fusion based spectral reconstruction, and found the best camera spectral response curves. Finally, we have gone beyond spectral reconstruction and examined the effect of spectral response fuctions for high-level task of scene classification.

研究分野：Computer Vision

キーワード：Spectral Imaging　Deep Learning　Filter Selection　Filter Design

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１．研究開始当初の背景

Hyperspectral imaging captures detailed light distribution along the wavelength axis. It is shown to be beneficial to remote sensing, medical diagnosis, industrial detection, and so on. For example, the tumor margin that is invisible to surgeon’s eyes can be better visualized in hyperspectral images, and the leak of invisible gas can be detected using spectral signals. To capture hyperspectral images, most existing devices are scanning based, that is, either to drive a line slit along one spatial dimension (pushbroom scan) or to continuously change narrow bandpass filters in front of a greyscale camera (filter scan). The key drawback is that scanning is slow, which prevents their application to dynamic scenes. For acceleration, scanning-free snapshot hyperspectral devices have been developed, by using for example fiber bundles or randomized aperture masks. Unfortunately, these devices are extremely limited in spatial resolution.

A computational hyperspectral reconstruction method from a multi-channel image is promising in conquering the drawbacks of aforementioned hyperspectral devices. However, existing multi-channel cameras, such as the widespread multi-sensor prism based RGB cameras or single-sensor Bayer filter array based RGB cameras, are best designed to mimic human color perception, thus their spectral response functions are not necessarily optimal for hyperspectral reconstruction. Therefore, the key scientific question here is ‘what are the best filter response functions for the purpose of multispectral-to-hyperspectral reconstruction, and how to find them in a computationally tractable way?’

２．研究の目的

The research purpose is to find the best spectral response functions for accurate multispectral-to-hyperspectral reconstruction using deep neural networks, and when necessary, implement the deeply learned filters by using film manufacturing technologies.

３．研究の方法

The core methodology is to model the filter spectral response functions into specialized convolutional layers and attach them onto a deep neural network that is designed for multispectral-to-hyperspectral reconstruction. Rather than fixing the response, we leave the filter responses as a design factor and automatically find the optimal filters through end-to-end learning. To accurately implement the designed filter response functions, the restrictions imposed by physical laws and the manufacturing process should be accounted in the designing process.

４．研究成果

During the project duration from 2019.4 to 2021.3, we have achieved the following major results.

4.1. Optimal Filter Selection from a Given Camera Response Database

It has been shown that the camera response functions play a key role in spectral reconstruction on the basis of sparse coding. However, it remains unknown whether this conclusion applies to deep learning based spectral reconstruction or not. Through brute force evaluation, we have confirmed that, the accuracy of spectral reconstruction depends on the camera response functions intrinsically, irrespective of the methods used for reconstruction. Furthermore, although it is feasible in principle to find the optimal filters from a given camera response database through brute force evaluation, this process is extremely time-consuming. To resolve this issue, we further model the filter selection process into a convolution layer, and introduce the nonnegative L1-norm penalty to pick up the best filter through end-to-end learning. As shown in Figure 1, the optimal camera can be correctly localized through our proposed technique by examining the non-zero element of the linear combination coefficients assigned to the cameras.

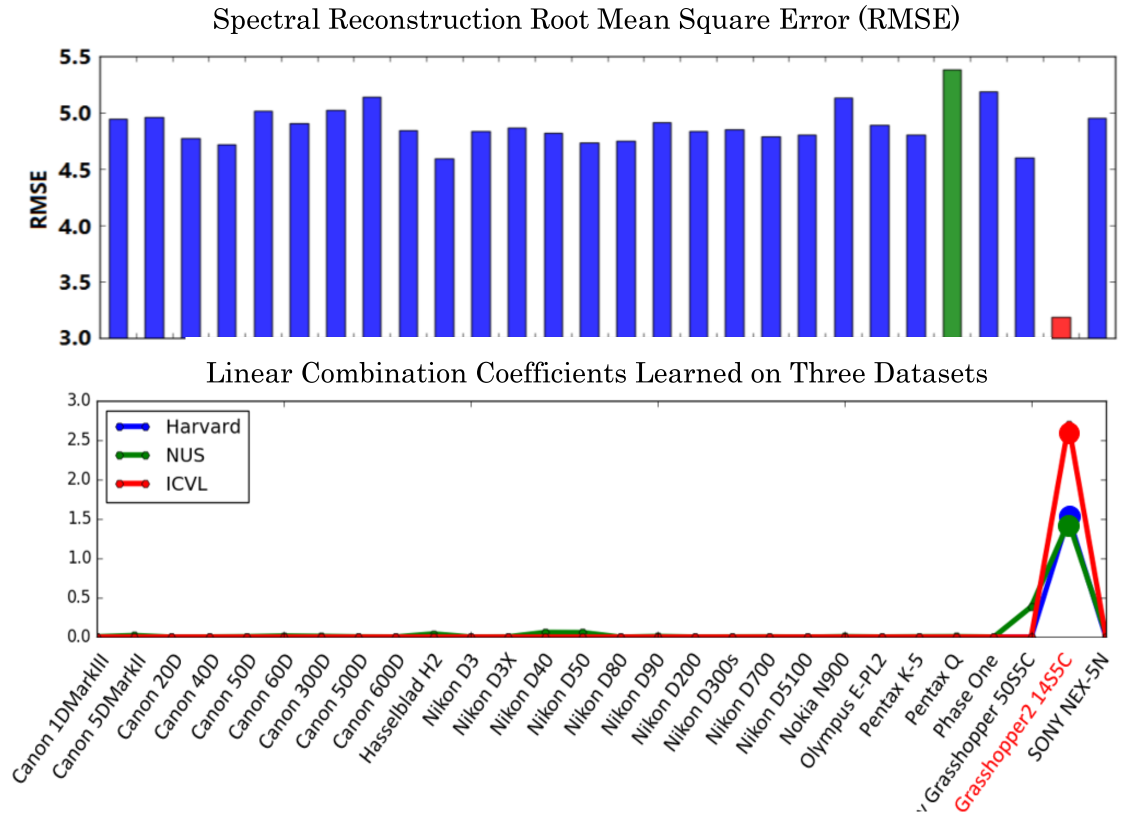
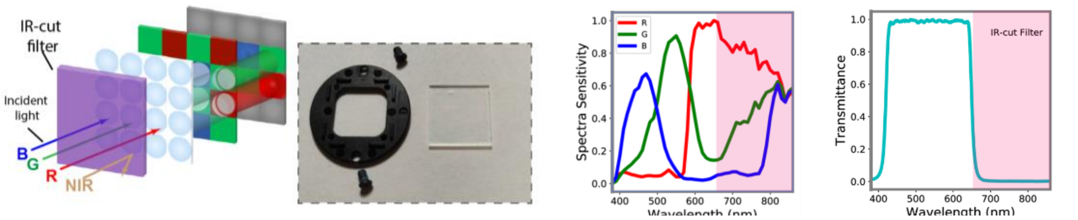


Figure 1. Optimal camera selection for spectral reconstruction through end-to-end deep learning. The subfigure above shows the spectral reconstruction error is obviously affected by the camera spectral response functions, and the Grasshopper2 14S5C camera is the best in the given camera database for the purpose of spectral reconstruction. The subfigure below shows that the best camera can be directly localized by examining the linear combination coefficients of the cameras, without brute force evaluation.

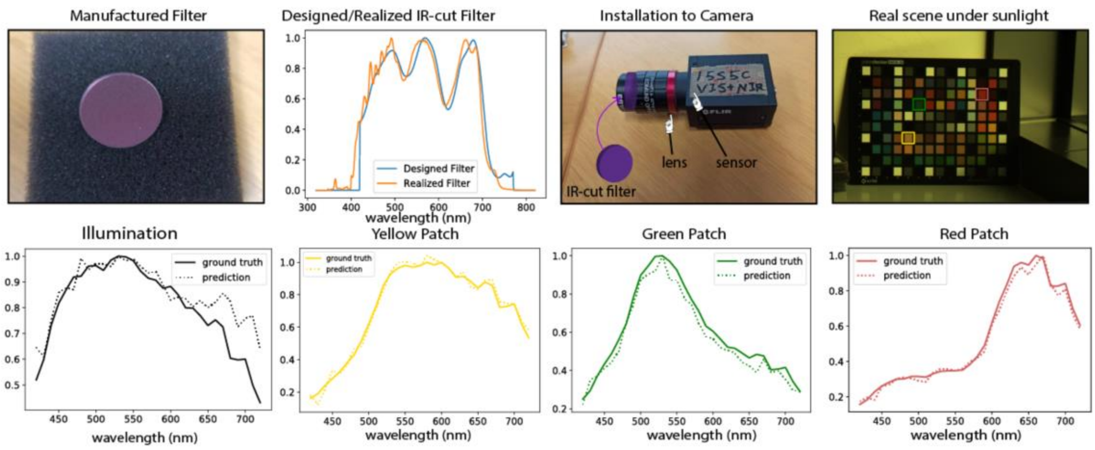
4.2. Tuning the IR-Cut Filter for Spectral Reconstruction from RGB

By examining the spectral response functions of the Grasshopper2 14S5C camera, we have noticed that its response in the 620~700nm range is much stronger than that of the other cameras. By further investigating the interior construction of commodity cameras, which usually place an IR-cut filter in front of the color sensor to block out the near infrared light, it becomes apparent to us that the response of the IR-cut filter has obvious effect on the spectral reconstruction. For example, some camera makers use an IR-cut filter, whose cut-off wavelength is 620nm, thus red light beyond 620nm can not reach the sensor, which is therefore inappropriate for spectral reconstruction in the 620~700nm range.

Therefore, we have tried to design the IR-cut filter response, so as to maximize the spectral reconstruction accuracy. We first design a network for spectral reconstruction and illumination spectrum estimation. Then, we measure the spectral response functions of a community camera after removing its IR-cut filter. We adapt the IR-cut response into a convolution layer, and let deep learning automatically design the optimal response for the sake of maximizing spectral reconstruction accuracy. To facilitate filter manufacturing, we introduce smooth constraints and nonnegative constraints. As a result, the designed IR-cut filter can be physically realized through film filter manufacturing technologies. The experiment results show that, the existing camera can be easily adapted by replacing the old IR-cut filter with our designed/realized IR-cut filter, and the accuracy of spectral reconstruction can be much improved.



(a) IR-cut Filter Mechanism (b) Response of the Sensor and IR-cut



(c) Realized IR-cut Filter and the Spectral Reconstruction using Adapted Camera

Figure 2. Turning the IR-cut filter for improved spectral reconstruction from RGB. (a) shows the IR-cut mechanism of commodity RGB cameras. (b) shows the response of the RGB sensor without the IR-cut filter, and the transmittance of the IR-cut filter. (c) shows the realized IR-cut filter and the easy adaption of the camera, which offers improved spectral reconstruction accuracy.

4.3. Optimal Filter Selection and Design for Fusion based Spectral Reconstruction

We have also investigated how filter selection and filter design will affect fusion based spectral reconstruction. In recent years, to fuse a low-resolution spectral image with a high-resolution RGB image is a popular way for spectral reconstruction. Compared with the reconstruction task from RGB, the fusion based method is less likely to be affected by the color metamerism issue. For example, the white LED lamp and the sunlight appear almost the same to the RGB camera, however, their spectra are quite different. To disambiguate the reconstruction, a spectral imager, although its spatial resolution is limited, will be very helpful.

We have first designed a novel multi-level and multi-scale spatial and spectral fusion network for spectral reconstruction. Compared with existing network structures, the proposed network is better at utilizing structural information embedded in the hybrid input, and the spectral reconstruction accuracy can be clearly improved, when trained and tested with the same protocols.

We have found that, similar to the case of RGB-based reconstruction, the spectral response functions of the RGB camera play a key role in fusion based spectral reconstruction. After introducing specialized convolutional layers for filter selection and design, we further developed schemes for automatic optimal filter selection and optimal filter design, and both achieved much improved results.

Our finding is that, as shown in Figure 3, the best camera for fusion based spectral reconstruction keeps unchanged as in the RGB-based reconstruction task. This indicates again that, the response in the 620~700nm range is very important for accurate spectral reconstruction in the full visible range from 400nm to 700nm.

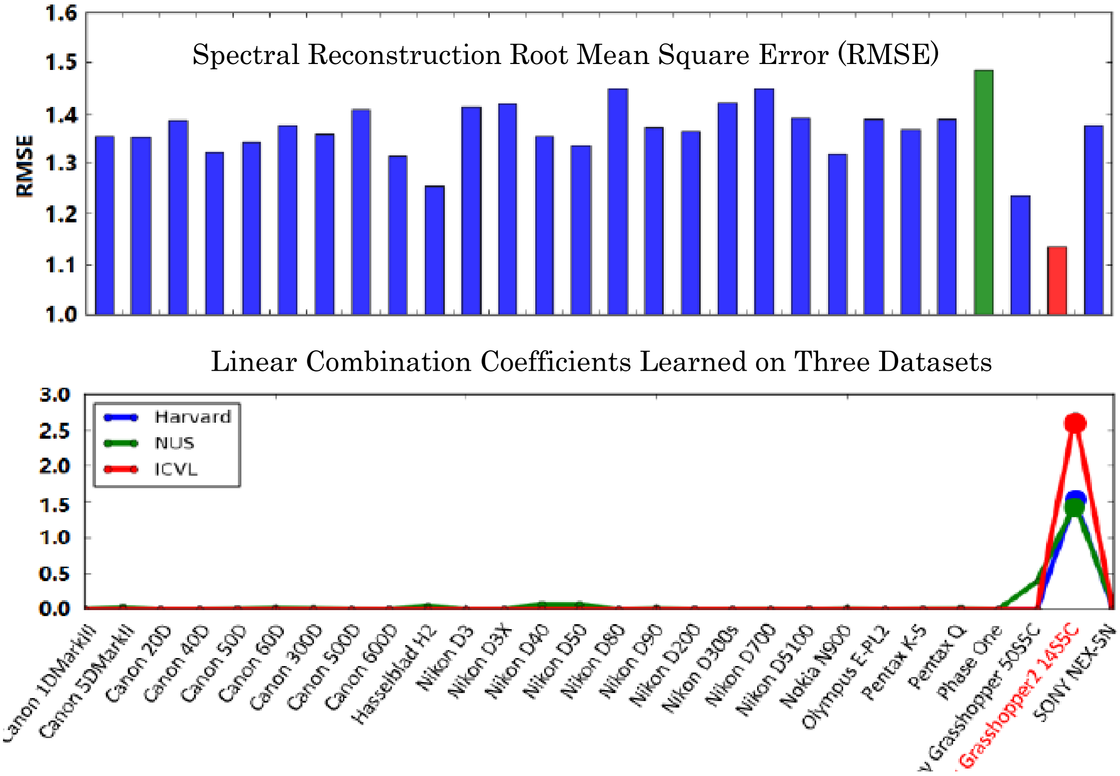


Figure 3. Optimal camera selection for fusion based spectral reconstruction. The subfigure above shows the spectral reconstruction error is obviously affected by the camera spectral response functions, and the Grasshopper2 14S5C camera is the best in the given camera database for the purpose of fusion based spectral reconstruction. The subfigure below shows that the best camera can be directly localized by examining the linear combination coefficients of the cameras, without brute force evaluation.

4.4. Optimal Filter for Spectra based Classification

Until now, we have focused on spectral reconstruction. However, in many application scenarios, scene understanding, such dimensionality reduction and object classification, is the ultimate goal. Therefore, it is interesting to investigate the effect of camera response functions on high-level classification tasks.

We first developed a deep learning based network for classification. Then, we designed the optimal camera spectral response functions to maximize the accuracy of classification. The designed curves are shown in Figure 4. We have verified that the optimally designed response functions can benefit classification accuracy.

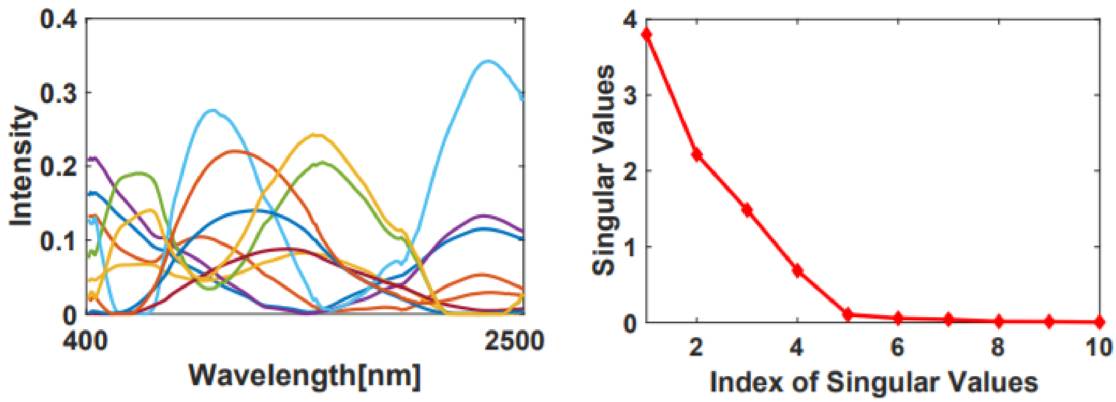


Figure 4. Optimal camera response functions for the Salinas Valley dataset in the case of 10 bands. The right subfigure shows the singular values of these 10 response curves, which indicates that the correlation of these 10 curves is not very strong.

５．主な発表論文等

〔雑誌論文〕　計4件（うち査読付論文　4件／うち国際共著　2件／うちオープンアクセス　2件）

１．著者名 Fu Ying、Zhang Tao、Zheng Yinqiang、Zhang Debing、Huang Hua	４．巻 na.
２．論文標題 Joint Camera Spectral Response Selection and Hyperspectral Image Recovery	５．発行年 2020年
３．雑誌名 IEEE Transactions on Pattern Analysis and Machine Intelligence	６．最初と最後の頁 na.
掲載論文のDOI（デジタルオブジェクト識別子） 10.1109/TPAMI.2020.3009999	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 該当する

１．著者名 Liu Zhe、Zheng Yinqiang、Han Xian-Hua	４．巻 21
２．論文標題 Deep Unsupervised Fusion Learning for Hyperspectral Image Super Resolution	５．発行年 2021年
３．雑誌名 Sensors	６．最初と最後の頁 2348～2348
掲載論文のDOI（デジタルオブジェクト識別子） 10.3390/s21072348	査読の有無 有
オープンアクセス オープンアクセスとしている（また、その予定である）	国際共著 －

１．著者名 Zou Yunhao、Fu Ying、Zheng Yinqiang、Li Wei	４．巻 12
２．論文標題 CSR-Net: Camera Spectral Response Network for Dimensionality Reduction and Classification in Hyperspectral Imagery	５．発行年 2020年
３．雑誌名 Remote Sensing	６．最初と最後の頁 3294～3294
掲載論文のDOI（デジタルオブジェクト識別子） 10.3390/rs12203294	査読の有無 有
オープンアクセス オープンアクセスとしている（また、その予定である）	国際共著 該当する

１．著者名 Han Xian-Hua、Zheng Yinqiang、Sun Jiande、Chen Yen-Wei	４．巻 16
２．論文標題 Hyperspectral Reconstruction with Redundant Camera Spectral Sensitivity Functions	５．発行年 2020年
３．雑誌名 ACM Transactions on Multimedia Computing, Communications, and Applications	６．最初と最後の頁 1～15
掲載論文のDOI（デジタルオブジェクト識別子） 10.1145/3386313	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 －

〔学会発表〕　計4件（うち招待講演　1件／うち国際学会　4件）

1．発表者名 Zhe Liu, Yinqiang Zheng, Xian-Hua Han
2．発表標題 Unsupervised Multispectral and Hyperspectral Image Fusion with Deep Spatial and Spectral Priors
3．学会等名 The Third Workshop on Machine Learning and Computing for Visual Semantic Analysis（国際学会）
4．発表年 2020年

1．発表者名 Bo Sun, Junchi Yan, Xiao Zhou, Yinqiang Zheng
2．発表標題 Turning the IR-Cut Filter for Illumination-aware Spectral Reconstruction from RGB
3．学会等名 IEEE Conference on Computer Vision and Pattern Recognition（招待講演）（国際学会）
4．発表年 2021年

1．発表者名 Ying Fu, Tao Zhang, Yinqiang Zheng, Debing Zhang, Hua Huang
2．発表標題 Hyperspectral Image Super-Resolution With Optimized RGB Guidance
3．学会等名 IEEE Conference on Computer Vision and Pattern Recognition（国際学会）
4．発表年 2019年

1．発表者名 Xian-Hua Han, Yinqiang Zheng, Yen-Wei Chen
2．発表標題 Multi-Level and Multi-Scale Spatial and Spectral Fusion CNN for Hyperspectral Image Super-Resolution
3．学会等名 IEEE International Conference on Computer Vision Workshop（国際学会）
4．発表年 2019年

〔図書〕　計0件

〔産業財産権〕

〔その他〕

This researches conducted in this project have further inspired us to explore data-driven imaging hardware design in the broad sense, including filter pattern design, aperature design, and phase mask design.

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

7．科研費を使用して開催した国際研究集会

〔国際研究集会〕　計0件

8．本研究に関連して実施した国際共同研究の実施状況

共同研究相手国	相手方研究機関			
米国	University of Southern California			
中国	Shanghai Jiao Tong University	Anhui Normal University	Beijing Institute of Technology	