# Optics and Computational Methods for Hybrid Resolution Spectral Imaging

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**Abstract.** The concept and computational methods for hybrid resolution spectral imaging (HRSI) are introduced. In HRSI, a high-resolution spectral image is reconstructed with combining a high-resolution RGB image and a low-resolution spectral image. An important difficulty in high-resolution spectral imaging is that the light-energy is reduced at the image sensor. Such problem can be solved by the hybrid resolution approach, since the image resolution and quality are mostly determined by the high-resolution RGB image, which can be captured by commercial high-performance cameras. Different reconstruction methods suitable for a hybrid resolution system are reviewed and the performance of those methods is discussed. The hybrid resolution spectral video system is also demonstrated.

**Keywords:** Spectral imaging · Multispectral imaging · Hybrid resolution · Color reproduction · Low-resolution spectral sensor · Piecewise Wiener · Regression

## 1 Introduction

A spectral imaging technology will be more widely adopted if high-resolution imagery can be acquired in video-rate with a compact and easy-to-handle imaging device.

Multispectral and hyperspectral imaging has been applied in remote-sensing [1], industrial inspection [2], security, biomedical imaging [3-5], digital archive of cultural heritage, and color reproduction [6-9]. Spectral video is also promising in those fields [10-12]. However, there are still some limitations in spectral video, such as the scanning time, the signal-to-noise (S/N) ratio, the less amount of light energy incident on an image sensor, and the processing of huge amount of data. There have been reported snapshot spectral camera systems recently [13-17], but it is yet difficult to capture high-resolution spectral video with a compact and handy camera system.

In the author's group, a hybrid-resolution spectral imaging (HRSI) have been developed for the solution to this problem. In HRSI, a low-spatial-resolution spectral (LR-Spec) image and a high-spatial-resolution 3-band image (HR-RGB) are captured simultaneously, and a spectral image with high-resolution in both spectral and spatial dimensions is reconstructed, as shown in fig. 1. The image reconstruction method is a key technology in HRSI, and this paper introduces some methods developed in our group, along with the optical systems for this purpose.

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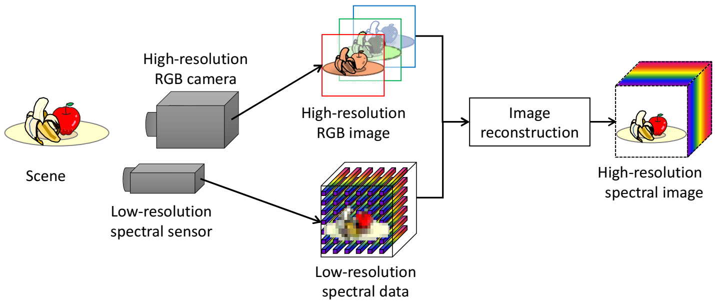



**Fig. 1.** The concept of hybrid resolution spectral imaging

## 2 Optical Systems for Spectral Imaging

Classical devices for capturing multispectral or hyperspectral images require spatial or spectral scanning, for example, filter-wheel cameras [6] and push-broom type sensors with diffraction grating [2]. Liquid crystal tunable filters [4] are also used for spectral scanning. Nevertheless, single-shot (or snapshot) imaging is expected for photographing moving objects or video imaging. Single-shot imaging is possible by using multiple sensors and dichroic-mirrors, and multiband video systems were demonstrated [11,12]. But the number of spectral channels is limited, as well as the optics design becomes difficult because the optical path becomes longer for the dichroic-mirror-based spectral imaging.

Advanced spectral imaging techniques suitable for video or single-shot imaging have been studied recently, such as Fourier Transform Imaging Spectrometer (FTIS) [13], Computed Tomography Imaging Spectrometer (CTIS) [14,15], Coded Aperture Snapshot Spectral Imaging (CASSI) [16], and Image Mapping Spectrometer (IMS) [17]. They enable the single-shot capture, but the spatial resolution is reduced.

For the application of spectral imaging to color reproduction, the display of realistic image is important, and high-resolution spectral imaging is crucial. One of the difficulties in high-resolution spectral imaging is the reduced light energy on the image sensor. It is known that the signal-to-noise (S/N) ratio is highest in the dichroic-mirror-based optical system, but the narrower the spectral bandwidth is, the less light intensity can be detected. In our previous 6-band high-definition video experiment [6, 11], the lens aperture was set larger so that enough light energy could be exposed to all the six image sensors. Then the depth of field became shallow, and the captured images were sensed as rather blurred. Moreover, the light intensity was sometimes not satisfactory yielding poor S/N ratio. Therefore, a method to breakthrough the trade-off between the spatial resolution and the image quality is needed for high-resolution spectral imaging.

## 3 Hybrid-Resolution Spectral Imaging System

The concept of HRSI is shown in fig. 1. It consists of two input devices; one with high-spatial-resolution but small number of spectral channels, and another one with high-spectral-resolution but low-spatial-resolution. Then the image data captured by those two devices are fused to derive an image with high spatial and spectral resolution. In the case of aiming at spectrum-based color reproduction, the former device with high-spatial-resolution can be a conventional RGB (Red, Green, Blue) camera.

The image quality including S/N ratio and sharpness is mainly depends on the former imaging device, i.e., a high-resolution RGB camera. It is possible to employ wide variety of high-performance digital cameras for both still and video imaging. The LR-Spec imaging device is used for improving the spectral and color fidelity, and thus this is a practical way to obtain high-resolution high-quality spectral images. Obviously there is a limitation if the target object is very small and has unique spectral characteristics, but in the application to color reproduction, the color difference in a small object is hardly noticed by human vision. Hence the hybrid-resolution approach is especially suitable for spectrum-based color imaging applications.

The idea of HRSI was originally introduced in remote sensing applications [18,19]. High-resolution spectral images are obtained by an image fusion of a low-resolution multispectral image and a panchromatic high-resolution image, or a low-resolution hyperspectral image and a high-resolution image with small number of bands.

We proposed the application of this concept to spectral color imaging [20-25]. In the earlier papers, the LR-Spec image was captured by scanning the fiber-based spectrometer. In [24, 25], we reported the hyperspectral video imaging with quasi-real-time spectrum-based color reproduction, using a low-resolution spectral sensor (LRSS) as described in chapter 5. Cao, Ma et. al., also reported spectral video system based on the similar approach [26, 27].

There are two ways for capturing HR-RGB and LR-Spec images, one is to use different cameras (a) and another way is to combine two systems using a beam splitter (b). In satellite or airborne imaging, (a) is suitable because the object is located very far from the two cameras, and the disparity can be ignored. If the objects are three-dimensional and located near the camera, the disparity between the two cameras should be taken into account. In such case, (b) seems to be better because the pixel-wise registration is possible. But the optical system becomes complicated, the amount of light energy is reduced by the beam splitter, and the handiness and the image quality are lost. If the method for reconstructing a spectral image is robust to the image registration error, the optical system (a) is preferable.

## 4 Reconstruction Methods for HRSI

The optical system as shown in fig.1 enables the simultaneous acquisition of an HR-RGB image and an LR-Spec image. Then, how can we reconstruct a spectral image with both spatially and spectrally high-resolution? In this subsection, let us firstly discuss the spectral estimation from the RGB data with the assistance of the spectral dataset obtained from the LR-Spec image.

**Spectral Estimation with the Aid of Spectral Measurements**

When the number of channels is not satisfactory high in a spectral imaging device, the spectral reconstruction is needed at each pixel of a spectral image. In color reproduction applications, it was reported that the surface spectra can be represented by small number of parameters by a linear model [28]. Then it is possible to reconstruct continuous spectrum from the measurement data of small number of spectral channels, e.g., RGB 3-channels. Various reconstruction techniques have been presented until now, including linear and nonlinear methods.

If we consider that continuous spectral data are sampled in N-wavelengths, then the spectral data can be represented as a vector in an N-dimensional space. In the linear model, the reconstructed spectra are located within the 3-dimensional (3D) subspace as shown in fig.2 (a). For example, in Wiener estimation method, which is one of commonly used technique, the 3D subspace for reflectance estimation is determined by the spectral sensitivity of the input device, the illuminant spectrum, and the covariance matrix of the object spectra. As it is not always possible to obtain the covariance matrix for specific objects to be imaged, a mathematical model is sometimes employed, e.g., the covariance matrix is derived based on Markov model [29]. In this case, the signals of closer wavelengths are considered to be more correlated, and the spectral distribution is assumed to be smooth. Although it is mostly true for various cases, it is more preferable employ the covariance matrix generated from the target object itself.

Thus, the LR-Spec data can be utilized to produce the covariance matrix of spectral characteristics of the target object, i.e., Wiener estimation [fig. 2 (b)]. It is also possible to derive the basis functions from the LR-Spec data by principal component analysis (PCA). The basis functions becomes adaptive to the target object as they are obtained from the measurement data. However, since only one set of three basis functions is used in the entire image, the accuracy of reconstructed spectra is limited especially when there are various objects that have different spectral characteristics in a scene.

**Spatio-Spectral MAP Estimation**

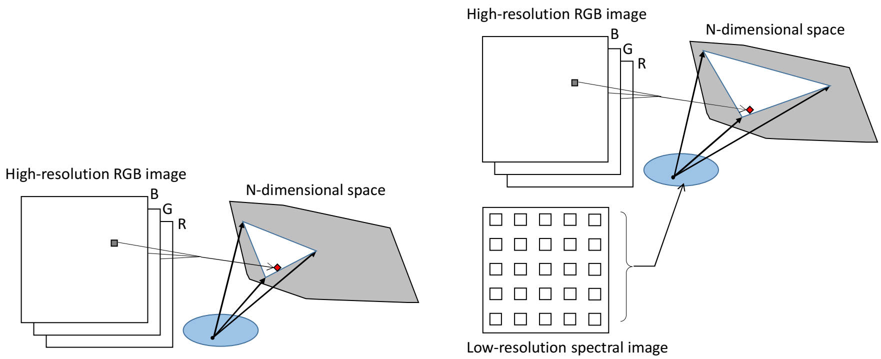
In fact, the LR-Spec image holds the information outside the subspace spanned by the three basis functions derived by the PCA of the covariance matrix. In order to make use of the information that lies outside the subspace, a method based on maximum a posteriori probability (MAP) was proposed [20]. This method is called spatio-spectral MAP (ss-MAP) estimation hereafter. The estimated spectral image $\hat{\mathbf{f}}$ is given by

$$\hat{\mathbf{f}} = \mathrm{argmax}_{\mathbf{f}}\ P(\mathbf{f}|\mathbf{g},\mathbf{r}) \tag{1}$$

where **f**, **g**, and **r** represent the original spectral distribution of the target object, the HR-RGB image, and the LR-Spec image, respectively. Under the assumption that the spatial and spectral correlation is separable, the solution of eq.(1) becomes the form:

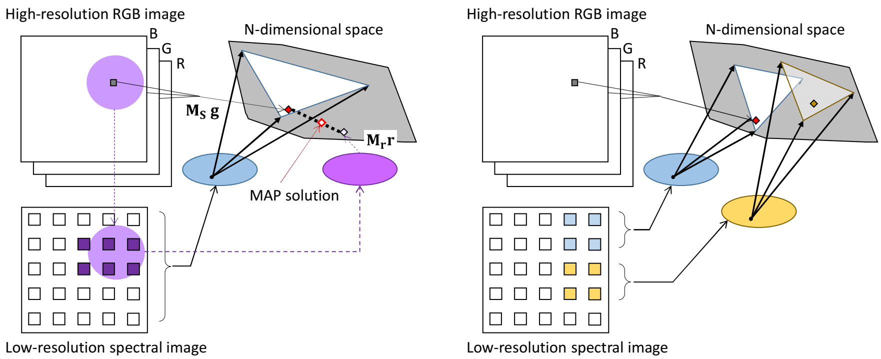
$$\hat{\mathbf{f}} = \mathbf{M_s}\,\mathbf{g} + \mathbf{M_r}\,\mathbf{r} \tag{2}$$

where $\mathbf{M}_s$ and $\mathbf{M}_r$ express the estimation operators based on spectral and spatial correlation, respectively. The first term is the same as the method described in the previous paragraph, shown in fig. 2 (b). The second term is the estimation in the ($N$–3) dimensional subspace that is orthogonal to the three basis functions, derived from the spatial correlation of the HR-RGB image [Fig. 3 (a)]. Therefore, the location information of the LR-Spec image is exploited, and the component that is orthogonal to the 3D subspace spanned by the basis functions can be determined by this method. A problem in this method is the calculation cost.



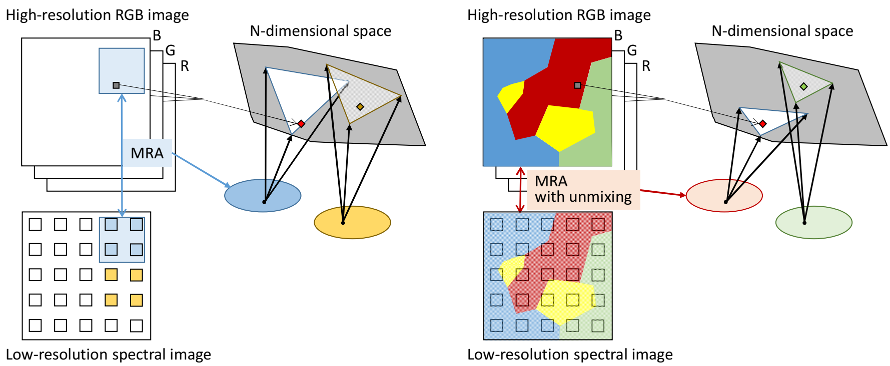

(a) (b)

**Fig. 2.** (a) Spectral estimation based on a linear model from an RGB image. (b) LR-Spec image is used to derive the optimal basis functions.




(a) (b)

**Fig. 3.** Schematic illustration of (a) MAP estimation and (b) piecewise Wiener estimation in hybrid resolution spectral imaging




(a) (b)

**Fig. 4.** Schematic illustration of modified MRA-based spectral estimation methods. (a) Locally weighted regression (LW-MRA), and (b) class-based regression with spectral unmixing.

**Piecewise Wiener Estimation**

Another way to overcome the limit of the 3D subspace is to use different sets of basis functions depending on the location in the image. Piecewise Wiener (PW) estimation technique utilize different estimation matrices derived from the spectral measurements near the target pixel, as shown in fig. 3 (b) [21]. Then the estimation accuracy is improved when multiple classes of objects are present in the image. The computational cost is not very high, where multiple matrices are prepared from the LR-Spec image and applied to each pixel of the HR-RGB image. Then it is possible to implement the method in real-time without using special dedicated hardware. In practice, adjacent blocks should be overlapped to avoid the block artifact at the boundary.

**Regression-Based Reconstruction Methods**

Multiple regression analysis (MRA) has also been applied to the spectral estimation from multiband or RGB data, and can be applied to HRSI. In contrast to the above methods like ss-MAP and PW estimation that employ the spectral sensitivity of the input device to derive estimation matrices, it is not needed in regression-based methods. It is beneficial as the accurate spectral sensitivity measurement is not an easy task.

To apply MRA to HRSI, the pixel correspondence is required. Since the pixel aperture of LRSS is often larger than the RGB imager, a virtual low-resolution RGB image is generated from its high-resolution version, to attain the correspondence in the low-resolution pixels. Then MRA is applied to derive a matrix for spectral estimation, and the matrix is applied to each pixel of the RGB image to generate a high-resolution spectral image. In principle, the performance is equivalent to the Wiener estimation of fig. 2 (b), except that the spectral sensitivity is not explicitly needed in MRA process.

It is also possible to apply the concept similar to the PW technique in MRA, which was reported in [25]. As shown in fig. 4 (a), the image is divided into multiple blocks, and the regression coefficient matrix is derived for each block. The spectral data from LRSS are weighted depending on the distance from the center of each block. Then different matrices are applied to every location in the image.

The method of fig. 4 (a) is based on the idea that the correlation of spectral characteristics is higher if two pixels are closer. However, there are often cases where multiple objects in the scene have same spectral characteristics. In such case, the spectral correlation is high even if multiple objects are apart from each other. Then a class-based reconstruction technique was proposed [22]. Fig. 4 (b) shows the overview of the method. Firstly an HR-RGB image is segmented based on the color information, where each segment is not necessarily aggregated in the image; multiple separated objects in the image can belong to the same class. Then the class of each pixel in the LR-Spec image is determined from the corresponding region in the image, and MRA is applied to each class. But there is a question: how do we handle the case when the pixel in the LR-Spec image is larger and corresponds to the pixels of multiple classes in HR-RGB image? In the method presented in [22], the spectral unmixing is applied to a pixel that belongs to multiple classes and MRA is adopted to the unmixed classes.

**Bilateral and Trilateral Interpolation**

Moreover, there have been reported hybrid systems for spectral video using bilateral and trilateral interpolation [26, 27]. The spectrum of a pixel in high-resolution spectral image is interpolated from neighboring pixels of LR-Spec data, with weighting based on the Euclidian distances in both the spatial domain and the RGB color space. In the video application, the interpolation was done in temporal direction as well after an optical flow is adopted. The interpolation technique is designed for the system in which the image set consists of RGB pixels with the spectral measurements and RGB pixels that do not have correspondence to the spectral data. It is expected to extend the interpolation method in future to the case when the pixel aperture sizes are different in RGB and spectral images, like the instances shown in figs. 2-4.

## 5 Experiments

**Performance of Different Reconstruction Methods**

In [21], the performance of the PW and ss-MAP estimation was compared and it was shown that the estimation accuracy was almost equivalent, while the computational cost in ss-MAP estimation was much higher. The accuracy of PW estimation was shown to be significantly higher than 3-band cameras without low-resolution spectral measurement, and Wiener estimation using the low-resolution spectral data. Although the accuracy depends on the image content, PW technique gives better results especially in the images that hold multiple objects of various colors. The results of the class-based regression method with spectral unmixing were reported in [22], where the performance is similar to PW, but sometimes better accuracy is achieved depending on the constituents in the image.

The accuracy of the image registration between HR-RGB and LR-Spec images is not serious in Wiener and PW techniques, where pixel-wise registration is needed in MRA or LW-MRA. Bilateral and trilateral interpolation technique also requires high-accuracy registration. In practice, a reconstruction method that is robust to the image registration error is expected.

**Experiments Using a Hybrid Resolution Spectral Video System**

We have demonstrated a hybrid resolution spectral video system [24] that employs a LRSS system [3], shown in fig. 5. It should be noted that the pixel size in the LRSS is considerably large, where the 2D fiber array corresponds a set of pixels. It is an important issue for achieving higher sensitivity in the LRSS. In the video system, the reproduction of a color or gray-scale image is not difficult even though spectral processing, because the spectral processing is linear and only 3×3 or 1×3 matrix multiplications are required for image reproduction. It is possible to reproduce an image with spectrum-based color reproduction and single wavelength image in almost real-time, and if a certain point on the image is clicked by a mouse, the spectral distribution at the pixel is exhibited in another window.

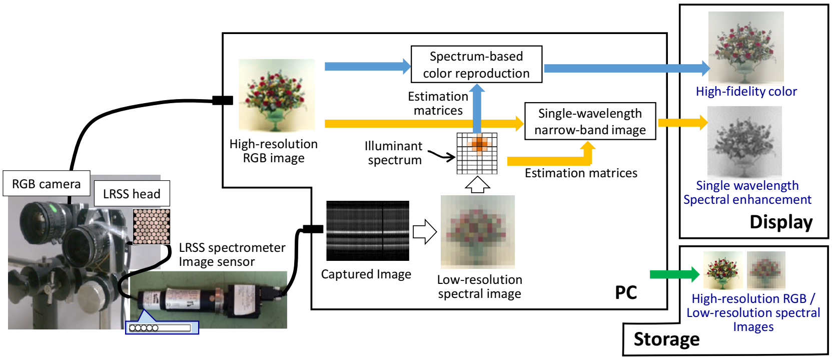



**Fig. 5.** The spectral data from 68 fibers are captured by an LRSS, and after the calibration and the rearrangement, a LR-Spec image is produced. In PW estimation or LW-MRA technique, 3×3 or 1×3 matrices are applied to the HR-RGB image as they are basically linear processing, thus the computational cost is not so high and real-time reproduction is possible.

Table 1 shows the results on the evaluation of color reproduction accuracy. The error was slightly large in PW estimation using LRSS data. We consider this unexpected larger error is caused by the error in the spectral sensitivity of the RGB camera. In MRA and LW-MRA, the spectral sensitivity data is not used in the estimation process, and the error became smaller. Additionally, the color differences are larger because the difference was calculated from objects that have color variation measured by a spectroradiometer and the HRSI system. Despite of those issues in the experiment, it can be confirmed that the LW-MRA gives the best performance among the tested methods. The image quality was basically determined by the HR-RGB camera, and good-quality results were obtained.

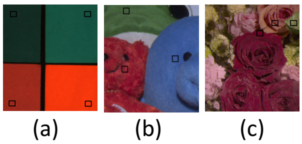



**Fig. 6.** (a)-(c) Three images used in the experiment. The small squares in the images indicate the regions used in the color difference calculations.

**Table 1.** Color estimation error (average CIELAB ΔE) in the estimated colors under D50 from the spectral images captured under artificial sunlight (Seric Solax XC-100AF). (a)-(c) indicate the images shown in figs. 6 (a)-(c).

| Image | Wiener (Markov) | Wiener (LRSS) | PW (LRSS) | MRA | LW-MRA |
|---|---|---|---|---|---|
| (a) | 13.1 | 13.0 | 9.6 | 7.5 | 3.4 |
| (b) | 12.5 | 9.1 | 8.1 | 5.5 | 5.2 |
| (c) | 12.4 | 7.9 | 5.6 | 8.8 | 5.5 |

## 6 Conclusion

This paper introduces the concept of HRSI and the algorithms for reconstructing a spectral image. The HRSI enables to reconstruct a high-resolution spectral image from LR-Spec and HR-RGB images. As the image quality mainly depends on the HR-RGB image in HRSI, it becomes possible to obtain high-resolution and high-quality spectral images by a single-shot. It should be mentioned that the hybrid resolution approach is not suitable for the application that requires to detect small regions with abnormal spectral characteristics that cannot be distinguished by the HR-RGB image.

From the review of different reconstruction methods and the experimental comparison presented in this paper, it is needed to undertake more comparative evaluations to explore a practical reconstructing method for HRSI. Then it is also expected to explore the applications of the hybrid-resolution systems that enables to capture high-resolution and high-quality spectral images.

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