Hyperspectral Image Fusion: A Comprehensive Review

IMLEX MSc Thesis

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Overview

1. Introduction
2. Related Work
3. Practical Application
4. Results & Discussion
5. Conclusion Work

Introduction

- Hyperspectral imaging (HSI) collects several images (bands) over a wide and continuous wavelength range.
- This forms a hyperspectral (HS) cube formed by 3 dimensions — 2 for the spatial position and 1 for the spectral coordinate (x, y, λ).[1]

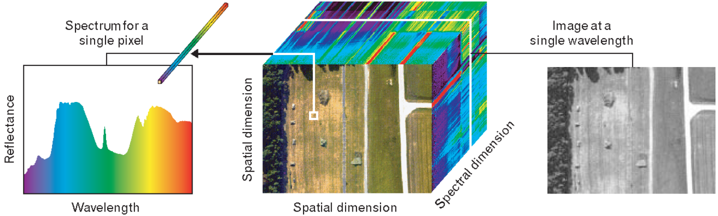


Figure: Representation of an hyperspectral cube (center) with a simultaneous illustration of a sample spatial (right) and spectral (left) data.

[1] Dimitris Manolakis, David Marden, Gary A Shaw, et al. "Hyperspectral image processing for automatic target detection applications". In: *Lincoln laboratory journal* 14.1 (2003), pp. 79–116.

Introduction - Motivation

- HSI has proven its usefulness with its rich spectral information, but lacks acutely in terms of spatial resolution.[2]
- This is caused by **hardware limitations** — a long exposure is necessary to collect enough photons while maintaining a good signal-to-noise ratio, leading to low spatial resolutions.

Problem

The **lack of spatial resolution** hinders the development of further HSI applications and diminishes the accuracy of the already existing ones.

Solution

Software-based approaches to improve the resolution of hyperspectral images.

[2] Naveed Akhtar, Faisal Shafait, and Ajmal Mian. "Sparse spatio-spectral representation for hyperspectral image super-resolution". In: *European conference on computer vision*. Springer. 2014, pp. 63–78.

Introduction - Scope and Objectives

- **Research, test and compare existing methods of spatial resolution enhancement** in hyperspectral images in a practical environment.
- Data analysis resulting from the HS image fusion processes:
  - **improves the applicability** of this technology across all the pre-existing applications;
  - allows for other **novel usages** that would otherwise not have been possible with the available low-resolution HS images.

Related Work

- Hyperspectral Super-Resolution (HSSR)
  - Single HS Image Super-Resolution (SHSR)
  - MS[3] and HS Image Fusion (HIF)
    - Spatial Unmixing
    - Linear Transformation
    - Pan-Sharpening Based
    - Matrix Factorization
    - Bayesian Based
    - Tensor Based
    - Deep Learning
    - Registration Simulation
  - Spatio Spectral Super-Resolution (SSSR)

[3] Multispectral

Related Work - Problem Formulation

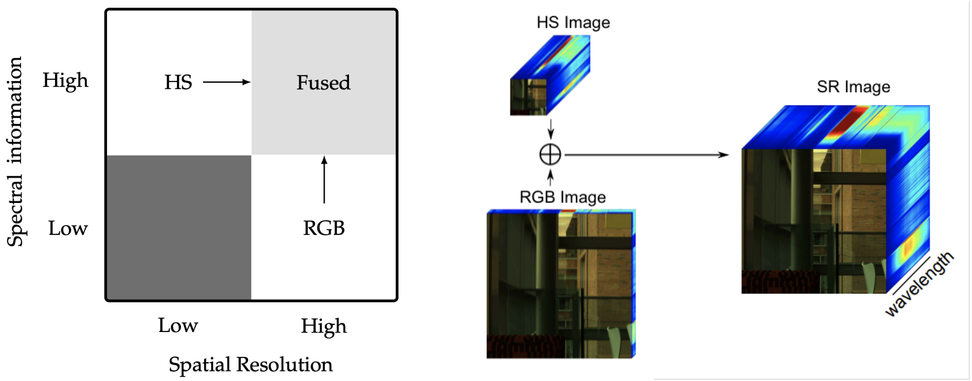
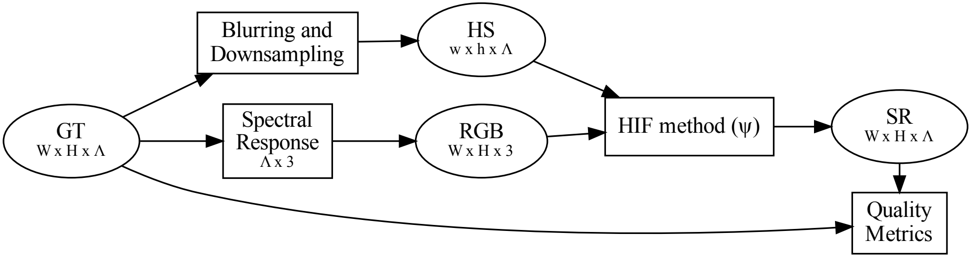


Figure: **Left:** Spatial vs spectral representation of the input and output data of HIF.
Right: Input and output diagram of a HIF method.

Related Work - Wald's Protocol[4]



[4] Lucien Wald, Thierry Ranchin, and Marc Mangolini. "Fusion of satellite images of different spatial resolutions: Assessing the quality of resulting images". In: *Photogrammetric engineering and remote sensing* 63.6 (1997), pp. 691–699.

Related Work - Datasets

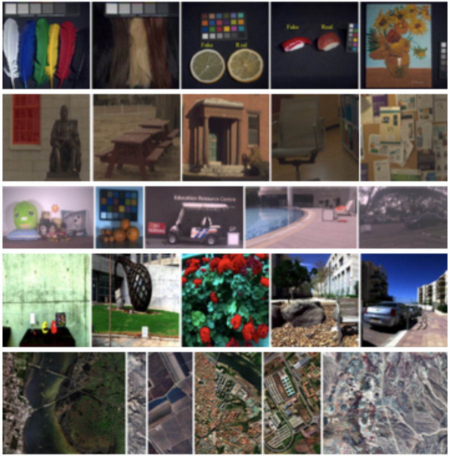


Figure: Sample images from several datasets. Each row contains images from a distinct dataset (from the top to the bottom): CAVE, Harvard, NUS, ICVL and EHU.

Related Work - Quality Metrics

Metric	Domain	Best Value
Total Error	Global	$\downarrow 0$
Root Mean Squared Error (RMSE)	Global	$\downarrow 0$
Relative Average Spectral Error (RASE)	Global	$\downarrow 0$
Erreur Relative Globale Adimensionnelle de Synthèse (ERGAS)	Global	$\downarrow 0$
Spatial Correlation Coefficient (SCC)	Spatial	$\uparrow 1$
Peak Signal-to-Noise Ratio (PSNR)	Global	$\uparrow$
Structural Similarity Index (SSIM)	Global	$\uparrow 1$
Multi-scale Structural Similarity Index (MS-SSIM)	Global	$\uparrow 1$
Block Sensitive - Peak Signal-to-Noise Ratio (PSNR-B)	Global	$\uparrow$
Universal Image Quality Index (UQI)	Global	$\uparrow 1$
Spectral Angle Mapper (SAM)	Spectral	$\downarrow 0$
Spectral Information Divergence (SID)	Spectral	$\downarrow$
Visual Information Fidelity (VIF)	Global	$\uparrow$
$Q2^n$	Global	$\uparrow$

Practical Application - Issues in HIF Testing

- **Lack of publicly available code** of HIF methods.
- Frequently, the **code is not run under the same conditions** due to:
  - Images being stored in **different formats** (`uint8`, `float`, among others).
  - **Different techniques** are used **to simulate input images** for Wald's protocol.
  - **Stabilizers being sometimes added** after an HIF method to improve results.
  - **Noisy bands** of HS datasets are removed with different criteria.
  - Using **distinct set of spatial scaling factors** and **different metrics** to compare results.
- Some methods require **knowledge of the point spread function (PSF) and/or spectral response function (SRF)** of the camera, instead of estimating those parameters (and as in a real-world scenario).

Summary

1. Different authors employ **different testing conditions** that lead to different results which are unfeasible to be directly compared with each other;
2. The **lack of real-world simulation conditions** further hinder the ecological validity of the results which are being presented.

Practical Application - Proposed Testing Protocol

- For a method to be fairly compared, its **code must be publicly available and run under the same conditions as its peers**, which means that:
  - Images are all in the same format (inc. data type);
  - Input images are simulated under the exact same conditions;
  - If results stabilizers are added, they should be tested for all methods (with the best alternative for each the method being selected, either with or without said stabilizer);
  - If noisy bands are removed for the computation of metrics, those exact bands are to be removed across all the methods in the same manner;
  - SRF and PSF parameters are estimated, emulating a real-world scenario;
  - The initial parameters are to be the ones proposed in the original paper, and should not be cherry-picked for each separate image.
- **Multiple spatial scaling factors** must be used together with **distinct datasets with different characteristics** - the images should include natural/artificial shapes, objects, colors; indoors/out- doors scenes; and remote sensing scenes from different continents in both urban and natural areas.

Practical Application - Implementation

GitHub Repository

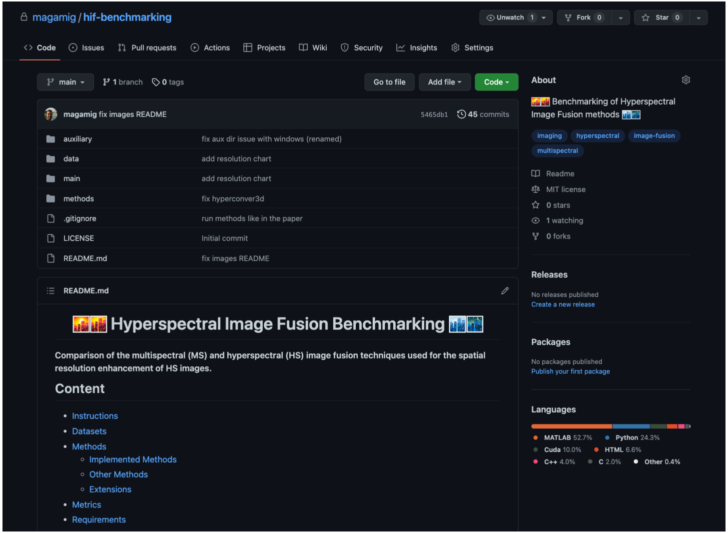
Following the previously described proposal, we developed a testing protocol for HIF methods: `https://github.com/magamig/hif-benchmarking/`.

- 91 HIF methods found in total
- 57 of those HIF methods had their code publicly available
- 15 of those HIF methods were implemented

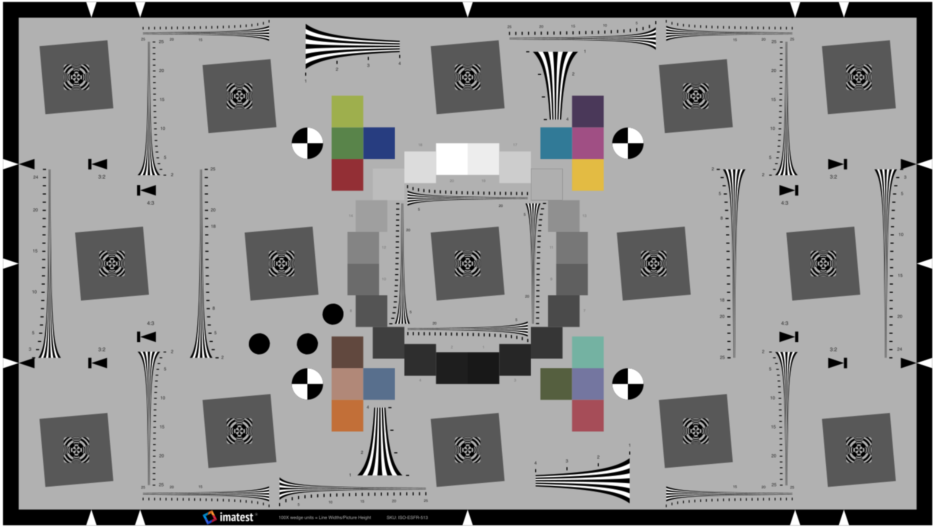
```
SCALINGS = [4,8,16]
DATASETS = ["CAVE","EHU","Harvard"]
METHODS = ["CNMF","FUSE","SFIM","GSA","GLP","GSOMP",\
    "NSSR","SupResPALM","CNNFUS","HySure","MAPSMM",\
    "LTTR","LTMR","CSTF","BayesianSparse"]

```

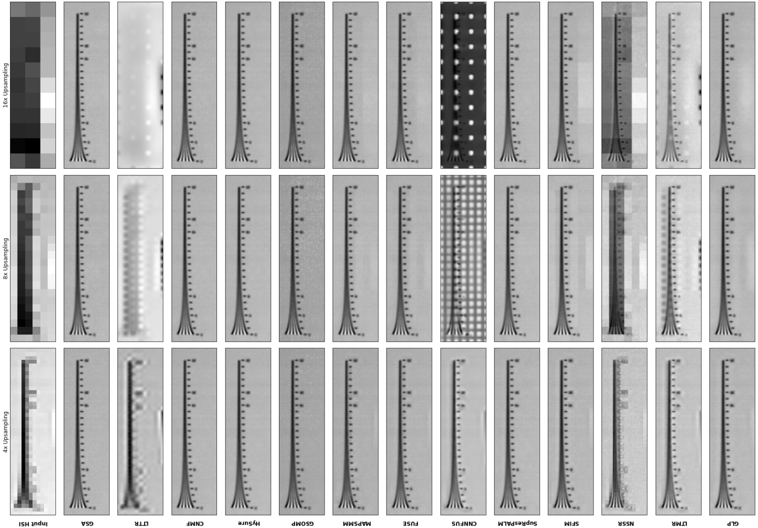
Practical Application - GitHub Repository



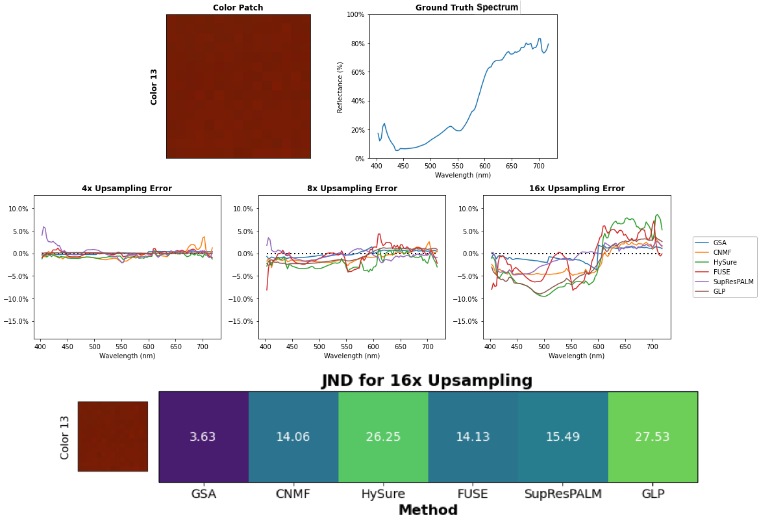
Results & Discussion - eSFR ISO 12233:2017



Results & Discussion - Preliminary Selection



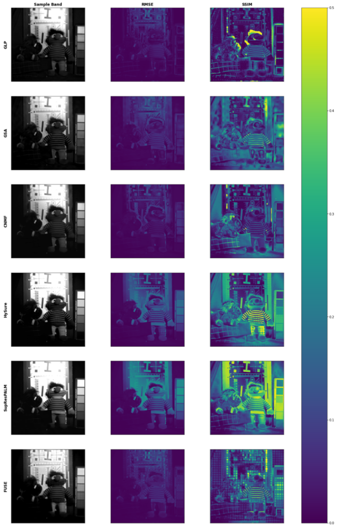
Results & Discussion - Preliminary Selection



Results & Discussion - Numerical Analysis (CAVE)

Scaling Factors	HIF Methods	Quality Metrics		
		SSIM ↑	SCC ↑	SAM ↓
4x	GLP	0.967	0.574	0.078
	GSA	0.870	0.518	0.173
	CNMF	0.918	0.487	0.143
	HySure	0.892	0.490	0.167
	SupResPALM	0.867	0.504	0.282
	FUSE	0.910	0.467	0.146
8x	GLP	0.945	0.569	0.105
	GSA	0.870	0.528	0.178
	CNMF	0.914	0.490	0.141
	HySure	0.863	0.494	0.209
	SupResPALM	0.867	0.506	0.282
	FUSE	0.879	0.458	0.181
16x	GLP	0.919	0.558	0.133
	GSA	0.867	0.529	0.186
	CNMF	0.903	0.479	0.148
	HySure	0.827	0.510	0.241
	SupResPALM	0.866	0.497	0.281
	FUSE	0.858	0.469	0.197

Results & Discussion - Visual Analysis (CAVE)



Conclusion

- We provide a **comprehensive review of the state-of-the-art of HIF**.
- The **shortcomings of existing HIF testing** protocols are presented, which the developed **generalized, fair, and extendable testing protocol** addresses.
- The **protocol is tested using the different methods, datasets, and spatial scaling factors** through a numerical and also a visual analysis of the output.

Summary

- **Testing conditions should be equal** across all methods and should emulate as good as possible the constraints encountered in the **real-world**.
- The selection of a HIF method is both **data- and task-dependant**.

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