SPATIO-SPECTRAL SUPER-RESOLUTION OF HYPERSPECTRAL IMAGES

Sadia Hussain Dar

Bharti School of Telecommunication Technology and Management

INDIAN INSTITUTE OF TECHNOLOGY DELHI

July 2024

Spatio-Spectral Super-resolution of Hyperspectral Images

by

Sadia Hussain Dar

Bharti School of Telecommunication Technology and Management

Submitted

in fulfillment of the requirements of the degree of Doctor of Philosophy

to the

INDIAN INSTITUTE OF TECHNOLOGY DELHI

July 2024

Dedicated to my father, mother, sister and the rest of my family for being my rock.

Certificate

This is to certify that the thesis entitled **"Spatio-Spectral Super-resolution of Hyperspectral Images"**, submitted by **Sadia Hussain Dar** to the Indian Institute of Technology Delhi, for the award of the degree of **Doctor of Philosophy**, is a record of the original, bona fide research work carried out by her under our supervision and guidance. The thesis has reached the standards fulfilling the requirements of the regulations related to the award of the degree.

The results contained in this thesis have not been submitted in part or in full to any other University or Institute for the award of any degree or diploma to the best of our knowledge.

Prof. Brejesh Lall
Department of Electrical Engineering,
Indian Institute of Technology Delhi.

Prof. B.K. Panigrahi
Department of Electrical Engineering,
Indian Institute of Technology Delhi.

Dr. Sanya Anees
Department of Electronics and Communication Engineering
NSUT Delhi.

Acknowledgements

I offer my heartfelt gratitude to the Almighty, Allah, for the countless blessings in life in terms of relationships, work, and everything in between. Thank you for granting me the opportunity to work in this enriching environment. His provision has exceeded my expectations, surrounding me with caring individuals who have consistently supported me. I extend sincere thanks to the many individuals whose guidance and support have been invaluable in achieving the completion of my Ph.D.

First and foremost, I extend my heartfelt appreciation to my Ph.D. supervisor, **Prof. Brejesh Lall**. Sir, you have made an indelible impact on my life, and for that, I am deeply grateful. Your steadfast support and unwavering encouragement have been instrumental throughout my tenure at IITD. Beyond imparting invaluable guidance in machine learning and computer vision, you have instilled in me a sense of resilience and determination. Your mentorship extended beyond academics, demonstrating care, appreciation, and recognition at every turn. Our countless discussions and mentoring sessions have not only refined my academic skills but also equipped me with critical thinking abilities and the confidence to tackle challenges creatively. You have transformed what could have been an anxious Ph.D. journey into a fulfilling and enjoyable experience. Thank you sincerely for everything.

I am also immensely grateful to **Prof. B.K. Panigrahi** and **Dr. Sanya Anees** for their contributions to my Ph.D. journey. Additionally, I extend my gratitude to the members of my Ph.D. School Research Committee, Prof. Monika Aggarwal, Prof. Sumantra Dutta Roy, and Prof. Sandeep Kumar, for their insightful feedback and constructive criticism.

In addition to the academic community, I am deeply grateful to my friends, Nargis Fayaz, Taniya Manzoor and Muneeb Ahmad. Their unwavering support and friendship have been a constant source of strength during various phases of my Ph.D. Their presence has imbued me with a sense of calmness and fortitude. Through our coffee break sessions, group activities, and shared moments of triumph and setbacks, Nargis, Taniya and Muneeb have been my sources of support. I also extend my sincere appreciation to Muhammad Taha Shah, and Sabrina Khurshid for their companionship. Their encouragement have been invaluable.

Furthermore, I would like to acknowledge the contributions of my dedicated lab mates - Naveenta Gautam, Tayeba Qazi, Darakshan Rashid, Sanhita Pathak, Megha Kataria, Dr. Mahroosh and Anushika Singh. I would also like to extend acknowledgment to my laboratory seniors, namely Dr. Vinay Kaushik, Dr. Ronak and Dr. Siddharth Srivastava for their valuable insights. Their collaborative spirit and collective pursuit of knowledge have fostered an enriching learning environment. From sharing research findings to providing technical assistance and offering words of encouragement, my lab mates have been invaluable partners in my academic journey. The diversity of perspectives, healthy competition and expertise within our lab has broadened my understanding of Machine learning and challenged me to think critically.

Special recognition to Ms. Anita Bisht, Mr. Dilip Jana and Ms. Savita for their exemplary support in managing administrative tasks and providing assistance whenever needed. Their professionalism, attention to detail are deeply appreciated.

Additionally, I thank the group I had at the hostel for fostering encouragement and perseverance throughout this journey. Last but not least, I extend my gratitude to all the interns who have contributed to my growth and development, enriching my experience and sharpening my skills as a leader. Their fresh perspectives, enthusiasm, and dedication to learning have not only benefited my research projects but also reminded me of the importance of mentorship.

To everyone who has supported, guided, and inspired me on this transformative journey, I offer my deepest gratitude. Your contributions have been invaluable, and I am profoundly grateful for your unwavering support.

Thank you all.

Sadia Hussain.

Abstract

Hyperspectral imaging (HSI) plays a pivotal role in various fields including remote sensing, agriculture, environmental monitoring, and medical diagnostics, owing to its ability to capture detailed spectral information across a wide range of wavelengths. However, one of the significant challenges in HSI is achieving high spatial resolution while maintaining spectral fidelity. The resolution of hyperspectral images is often constrained by factors such as sensor limitations, atmospheric conditions, and imaging geometry. Consequently, there exists a fundamental trade-off between improving spatial resolution and preserving spectral information. Enhancing resolution in hyperspectral images is crucial as it enables the identification and classification of fine spatial features, enhances the interpretability of data, and facilitates more accurate analysis and decision-making. However, the process of resolution enhancement must navigate the delicate balance between increasing spatial detail and minimizing spectral distortion or noise, which requires sophisticated methodologies and careful consideration of trade-offs.

The primary objective of this thesis is to address the inherent limitations of spectral and spatial resolution in hyperspectral images by employing super-resolution techniques. Super-resolution methods aim to enhance the resolution of images beyond the limitations of the sensor, thereby improving the clarity and detail of both spectral and spatial information. Specifically, this thesis focuses on developing innovative approaches to achieve higher spectral resolution in synthetic hyperspectral datasets and enhance spatial resolution in hyperspectral images. By leveraging super-resolution techniques, the goal is to produce high-quality hyperspectral images with enhanced spectral fidelity and finer spatial detail, thereby advancing the capabilities of hyperspectral imaging for various applications.

In this thesis we propose to construct a method using RGB image as input and synthesize a 31-channel HSI image as an output (Chapter 3). This spectral super-resolution is performed used adaptive receptive fields leveraging a deep learning architecture. On similar lines we construct another method from a 3 channel RGB input to 31 channel HSI output using neural network based filtering. This encompasses use of depth separable networks in HSI framework (Chapter 4).

Alternatively, we emphasize the use of grouping bands according to the reflectance spectra of HSI, which helps in effectively utilising the feature construction policy. Using a step by step process of feature reconstruction using shallow and deep feature extraction we perform single image super-resolution technique (Chapter 5). Consequently using a stronger deep feature extraction pipeline one can achieve improved super-resolution results of HSI (Chapter 6).

In conclusion, this thesis explores the domain of hyperspectral imaging with a particular emphasis on enhancing both spectral and spatial resolutions using super-resolution techniques. Through comprehensive exploration, we have extended our proposed methods for improved resolution, paving the way for more accurate and detailed reconstructions. Furthermore, experiments conducted on simulated datasets have showcased the efficacy of our methods, surpassing state-of-the-art techniques in terms of both spectral and spatial resolution enhancement. This research contributes to advancing the field of hyperspectral imaging, offering promising avenues for future studies and applications in various domains.

सार

हाइपरस्पेक्ट्रल इमेजिंग (एचएसआई) रिमोट सहित विभिन्न क्षेत्रों में महत्वपूर्ण भूमिका निभाती है इसके कारण संवेदन, कृषि, पर्यावरण निगरानी और चिकित्सा निदान तरंग दैर्ध्य की एक विस्तृत श्रृंखला में विस्तृत वर्णक्रमीय जानकारी प्राप्त करने की क्षमता। हालाँकि, एचएसआई में महत्वपूर्ण चुनौतियों में से एक उच्च स्थानिक रिज़ॉल्यूशन प्राप्त करना है वर्णक्रमीय निष्ठा बनाए रखते हुए। हाइपरस्पेक्ट्रल छवियों का रिज़ॉल्यूशन अक्सर होता है सेंसर सीमाओं, वायुमंडलीय स्थितियों और छवि जैसे कारकों द्वारा बाधित आईएनजी ज्यामिति. नतीजतन, सुधार के बीच एक बुनियादी समझौता मौजूद है स्थानिक संकल्प और वर्णक्रमीय जानकारी का संरक्षण। हाई में रिज़ॉल्यूशन बढ़ाना- परिप्रेक्ष्य छवियां महत्वपूर्ण हैं क्योंकि यह सूक्ष्मता की पहचान और वर्गीकरण को सक्षम बनाती हैं स्थानिक विशेषताएं, डेटा की व्याख्या को बढ़ाती हैं, और अधिक संचय की सुविधा प्रदान करती हैं- दर विश्लेषण और निर्णय लेना। हालाँकि, संकल्प वृद्धि की प्रक्रिया स्थानिक विवरण बढ़ाने और न्यूनतम करने के बीच नाजुक संतुलन बनाना होगा वर्णक्रमीय विकृति या शोर, जिसके लिए परिष्कृत पद्धतियों और सावधानी की आवश्यकता होती है व्यापार-विनिमय पर विचार.

इस थीसिस का प्राथमिक उद्देश्य विशिष्टता की अंतर्निहित सीमाओं को संबोधित करना है- सुपर-रिज़ॉल्यूशन को नियोजित करके हाइपरस्पेक्ट्रल छवियों में ट्राल और स्थानिक रिज़ॉल्यूशन तकनीकें. सुपर-रिज़ॉल्यूशन विधियों का उद्देश्य छवियों के रिज़ॉल्यूशन को बढ़ाना है- सेंसर की सीमाओं से परे, जिससे दोनों की स्पष्टता और विवरण में सुधार हुआ वर्णक्रमीय और स्थानिक जानकारी. विशेष रूप से, यह थीसिस विकसित करने पर केंद्रित है- सिंथेटिक हाइपरस्पेक्ट्रल में उच्च वर्णक्रमीय रिज़ॉल्यूशन प्राप्त करने के लिए नवीन दृष्टिकोण डेटासेट और हाइपरस्पेक्ट्रल छवियों में स्थानिक रिज़ॉल्यूशन को बढ़ाना। लाभ उठाकर सुपर-रिज़ॉल्यूशन तकनीकों का लक्ष्य उच्च-गुणवत्ता वाले हाइपरस्पेक्ट्रल इमेज का उत्पादन करना है- बढ़ी हुई वर्णक्रमीय निष्ठा और बेहतर स्थानिक विवरण के साथ युग, जिससे प्रगति हो रही है विभिन्न अनुप्रयोगों के लिए हाइपरस्पेक्ट्रल इमेजिंग की क्षमताएं।

इस थीसिस में हम इनपुट के रूप में आरजीबी छवि का उपयोग करके एक विधि बनाने का प्रस्ताव करते हैं आउटपुट के रूप में 31-चैनल एचएसआई छवि को संश्लेषित करें (अध्याय 3)। यह वर्णक्रमीय सुपर- रिज़ॉल्यूशन गहन शिक्षण का लाभ उठाते हुए अनुकूली ग्रहणशील क्षेत्रों का उपयोग करके किया जाता है वास्तुकला। इसी तर्ज पर हम 3 चैनल आरजीबी से एक और विधि का निर्माण करते हैं तंत्रिका नेटवर्क आधारित फ़िल्टरिंग का उपयोग करके 31 चैनल एचएसआई आउटपुट में इनपुट। यह सहयोग- एचएसआई ढांचे में गहराई से अलग करने योग्य नेटवर्क का उपयोग पास करता है (अध्याय 4)।

वैकल्पिक रूप से, हम परावर्तन के अनुसार समूहीकरण बैंड के उपयोग पर जोर देते हैं एचएसआई का स्पेक्ट्रा, जो फीचर निर्माण नीति का प्रभावी ढंग से उपयोग करने में मदद करता है। उथले और गहरे फीचर का उपयोग करके फीचर पुनर्निर्माण की चरण-दर-चरण प्रक्रिया का उपयोग करना निष्कर्षण हम एकल छवि सुपर-रिज़ॉल्यूशन तकनीक (अध्याय 5) करते हैं। कॉन्से- लगातार एक मजबूत गहरी सुविधा निष्कर्षण पाइपलाइन का उपयोग करके कोई भी सुधार प्राप्त कर सकता है एचएसआई के सुपर-रिज़ॉल्यूशन परिणाम (अध्याय 6)।

निष्कर्ष में, यह थीसिस हाइपरस्पेक्ट्रल इमेजिंग के क्षेत्र की खोज करती है- सुपर- का उपयोग करके वर्णक्रमीय और स्थानिक दोनों रिज़ॉल्यूशन को बढ़ाने पर विशेष जोर दिया गया समाधान तकनीकें. व्यापक अन्वेषण के माध्यम से, हमने अपना विस्तार किया है बेहतर समाधान के लिए प्रस्तावित तरीके, अधिक सटीक और समाधान का मार्ग प्रशस्त करते हैं पूंछ पुनर्निर्माण. इसके अलावा, सिम्युलेटेड डेटासेट पर प्रयोग किए गए अत्या-धुनिक तकनीकों को पार करते हुए, हमारे तरीकों की प्रभावशीलता का प्रदर्शन किया है वर्णक्रमीय और स्थानिक रिज़ॉल्यूशन वृद्धि दोनों के संदर्भ में। यह शोध सह- हाइपरस्पे-क्ट्रल इमेजिंग के क्षेत्र को आगे बढ़ाने और आशाजनक रास्ते पेश करने के लिए धन्यवाद विभिन्न डोमेन में भविष्य के अध्ययन और अनुप्रयोगों के लिए।

Contents

List of Figures

List of Tables

Abbreviations

CAVE	**C**olumbia **A**dvanced **V**ision and **E**lectromagnetic
cGAN	conditional **G**enerative **A**dversarial **N**etwork
CNN	**C**onvolutional **N**eural **N**etworks
DCNN	**D**eep **C**onvolutional **N**eural **N**etworks
DL	**D**eep **L**earning
DRCN	**D**eeply **R**ecursive **C**onvolutional **N**etwork
DS-CNN	**D**epth **S**eperable **CNN**
E-FMNet	**E**xtending **F**unction **M**ixture **N**etwork
EnMAP	**E**nvironmental **M**apping and **A**nalysis **P**rogram
EOS	**E**arth **O**bserving **S**ystem
ESA	**E**uropean **S**pace **A**gency
FMNet	**F**unction **Mixture B**lock
FNN	**F**eedforward **N**eural **N**etwork
GOES	**G**eostationary **O**perational **E**nvironmental **S**atellites
HR	**H**igh **R**esolution
HyspIRI	**H**yperspectral **I**nfrared **I**mager
HSI	**H**yperspectral **I**mage
ILSVRC	**I**mageNet **L**arge **S**cale **V**isual **R**ecognition **C**hallenge
JPSS	**J**oint **P**olar **S**atellite **S**ystem
K-SVD	**K**-means **S**ingular **V**alue **D**ecomposition
LI	**L**inear **I**nterpolator

LR	**L**ow **R**esolution
MAE	**M**ean **A**bsolute **E**rror
MODIS	**MOD**erate Resolution **I**maging **S**pectroradiometer
MSI	**M**ulti **S**pectral **I**nstrument
MSS	**M**ulti- **S**pectral **S**canner
NIR	**N**ear **I**nfra **R**ed
NLP	**N**atural **L**anguage **P**rocessing
NN	**N**eural **N**etworks
NTIRE	**N**ew **T**rends in **I**mage **R**estoration and **E**nhancement
OLI	**O**perational **L**and **I**mager
OMP	**O**rthogonal **M**atching **P**ursuit
PAN	**PAN**chromatic
PSNR	**P**eak **S**ignal to **N**oise **R**atio
RMSE	**R**oot **M**ean **S**quare **E**rror
RNN	**R**ecurrent **N**eural **N**etworks
ROS	**R**ank **O**rder **S**tatistics
SA	**S**elf **A**ttention
SAM	**S**pectral **A**ngle **M**apper
SAR	**S**ynthetic **A**perture **R**adar
SISR	**S**ingle **I**mage **S**uper **R**esolution
SOTA	**S**tate **O**f **T**he **A**rt
SPOT	**S**atellite **P**our l'**O**bservation de la **T**erre
SRCNN	**S**uper **R**esolution **C**onvolutional **N**eural **N**etwork
SRF	**S**pectral **R**esponse **F**unction
SSIM	**S**tructural **S**imilarity **I**index
SSR	**S**pectral **S**uper **R**esolution
SWIN	**S**hifted **WIN**dow
SWIR	**S**hort **W**ave **I**nfrared

swinIR	swin **I**mage **R**estoration
SWUNet	**S**hifted **W**indow **U** **N**etwork
TIR	**T**hermal **I**nfra **R**ed
TM	**T**hematic **M**apper
UAV	**U**nmanned **A**erial **V**ehicle
VT	**V**ision **T**ransformer
VGG	**V**isual **G**eometry **G**roup
VSWIR	**V**isible to **S**hort **W**ave **I**nfrared