Introduction

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The Challenge

From time immemorial, man has had the urge to see the unseen, to peer beneath the earth, and to see distant bodies in the heavens. This primordial curiosity embedded deep in the psyche of humankind, led to the birth of satellites and space programs. Satellite images, due to their synoptic view, map like format, and repetitive coverage are a viable source of gathering extensive information. In recent years, the extraordinary developments in satellite remote sensing have transformed this science from an experimental application into a technology for studying many aspects of earth sciences. These sensing systems provide us with data critical to weather prediction, agricultural forecasting, resource exploration, land cover mapping and environmental monitoring, to name a few. In fact, no segment of society has remained untouched by this technology.

Over the last few years, there has been a remarkable increase in the number of remote sensing sensors on-board various satellite and aircraft platforms. Noticeable is the availability of data from hyperspectral sensors such as AVIRIS, HYDICE, HyMap and HYPERION. The hyperspectral data together with geographical information system (GIS) derived ancillary data form an exceptional spatial database for any scientific study related to Earth's environment. Thus, significant advances have been made in remote sensing data acquisition, storage and management capabilities.

The availability of huge spatial databases brings in new challenges for the extraction of quality information. The sheer increase in the volume of data available has created the need for the development of new techniques that can automate extraction of useful information to the greatest degree. Moreover, these techniques need to be objective, reproducible, and feasible to implement within available resources (DeFries and Chan, 2000). A number of image analysis techniques have been developed to process remote sensing data with varied amounts of success. A majority of these techniques have been standardized and implemented in various commercial image processing software systems such as ERDAS Imagine, ENVI and ER Mapper etc. These techniques are suitable for the processing of multispectral data but have limitations when it comes to an efficient processing of the large amount of hyperspectral data available in hundreds of bands. Thus, the conventional techniques may be inappropriate for information extraction from hyperspectral, multi-source, multi-sensor and multi-temporal data sets.

A number of textbooks on conventional digital processing of remote sensing data are available to the academic community (e. g. Jensen 1996; Richards and Jia 1999; Mather 1999; Campbell 2002). These deal with the basic digital image processing techniques together with fundamental principles of remote sensing technology. They are excellent resources for undergraduate and beginning graduate-level teaching. However, the researchers and graduate students working on the development and application of advanced techniques for remote sensing image processing have to depend on texts available in electrical engineering, and computer science literature, which do not focus on remote sensing data. This book contains chapters written by authors with backgrounds in different disciplines and thus attempts to bridge this gap. It addresses the recent developments in the area of image registration, fusion and change detection, feature extraction, classification of remote sensing data and accuracy assessment. The aim of the book is to introduce the reader to a new generation of information extraction techniques for various image processing operations for multispectral and particularly hyperspectral data. We expect that the book will form a useful text for graduate students and researchers taking advanced courses in remote sensing and GIS, image processing and pattern recognition areas. The book will also prove to be of interest to the professional remote sensing data users such as geologists, hydrologists, ecologists, environmental scientists, civil and electrical engineers and computer scientists. In addition to remote sensing, the algorithms presented will have far-reaching applicability in fields such as signal processing and medical imaging.

What is Hyperspectral Imaging?

Since the initial acquisition of satellite images, remote sensing technology has not looked back. A number of earth satellites have been launched to advance our understanding of Earth's environment. The satellite sensors, both active and passive, capture data from visible to microwave regions of the electromagnetic spectrum. The multispectral sensors gather data in a small number of bands (also called features) with broad wavelength intervals. No doubt, multispectral sensors are innovative. However, due to relatively few spectral bands, their spectral resolution is insufficient for many precise earth surface studies.

When spectral measurement is performed using hundreds of narrow contiguous wavelength intervals, the resulting image is called a *hyperspectral image*, which is often represented as a *hyperspectral image cube* (see Fig. 1) (JPL, NASA). In this cube, the x and y axes specify the size of the images, whereas the z axis denotes the number of bands in the hyperspectral data. An almost continuous spectrum can be generated for a pixel and hence hyperspectral imaging is also referred to as imaging spectrometry. The detailed spectral response of a pixel assists in providing accurate and precise extraction of information than is obtained from multispectral imaging. Reduction in the cost of sensors as well as advances in data storage and transmission technolo-

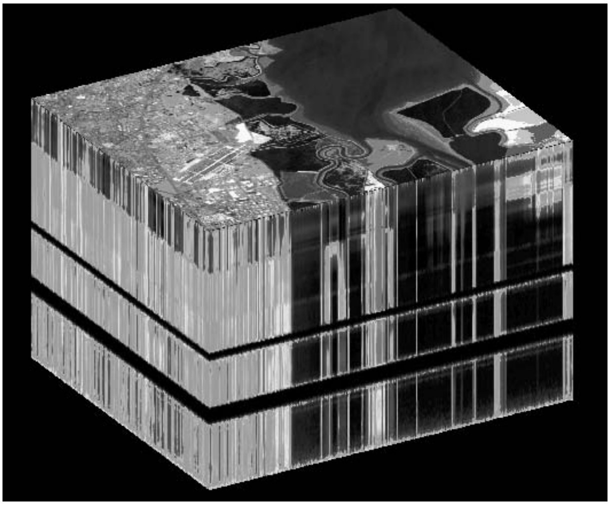

Fig. 1. The hyperspectral cube (source: http://aviris.jpl.nasa.gov/html/aviris.cube.html). For a colored version of this figure, see the end of the book

gies have made the hyperspectral imaging technology more readily available. Much like improvements in spectral resolution, spatial resolution has also been dramatically increased by the installation of hyperspectral sensors on aircrafts (airborne imagery), opening the door for a wide array of applications.

Nevertheless, the processing of hyperspectral data remains a challenge since it is very different from multispectral processing. Specialized, cost effective and computationally efficient procedures are required to process hundreds of bands acquiring 12-bit and 16-bit data. The whole process of hyperspectral imaging may be divided into three steps: preprocessing, radiance to reflectance transformation and data analysis.

Preprocessing is required for the conversion of raw radiance into at-sensor radiance. This is generally performed by the data acquisition agencies and the user is supplied with the at-sensor radiance data. The processing steps involve operations like spectral calibration, geometric calibration and geocoding, signal to noise adjustment, de-striping etc. Since, radiometric and geometric accuracy of hyperspectral data vary significantly from one sensor to the other, the users are advised to discuss these issues with the data providing agencies before the purchase of data.

Further, due to topographical and atmospheric effects, many spectral and spatial variations may occur in at-sensor radiance. Therefore, the at-sensor data need to be normalized in the second step for accurate determination of the reflectance values in difference bands. A number of atmospheric models and correction methods have been developed to perform this operation. Since the focus of this book is on data analysis aspects, the reader is referred to (van der Meer 1999) for a more detailed overview of steps 1 and 2.

Data analysis is aimed at extracting meaningful information from the hyperspectral data. A limited number of image analysis algorithms have been developed to exploit the extensive information contained in hyperspectral imagery for many different applications such as mineral mapping, military target detection, pixel and sub-pixel level land cover classification etc. Most of these algorithms have originated from the ones used for analysis of multispectral data, and thus have limitations. A number of new techniques for the processing of hyperspectral data are discussed in this book. Specifically, these include techniques based on independent component analysis (ICA), mutual information (MI), Markov random field (MRF) models and support vector machines (SVM).

Structure of the Book

This book is organized in three parts, each containing several chapters. Although it is expected that the reader is familiar with the basic principles of remote sensing and digital image processing, yet for the benefit of the reader, two overview chapters one on hyperspectral sensors and the other on conventional image processing techniques are provided in the first part. These chapters are introductory in nature and may be skipped by readers having sufficient relevant background. In the second part, we have introduced the theoretical and mathematical background in four chapters. This background is valuable for understanding the algorithms presented in later chapters. The last part is focused on applications and contains six chapters discussing the implementation of these techniques for processing a variety of multi and hyperspectral data for image registration and feature extraction, image fusion, classification and change detection. A short bibliography is included at the end of each chapter. Colored versions of several figures are included at the end of the book and this is indicated in figure captions where appropriate.

Part I: General

Chapter 1 provides a description of a number of hyperspectral sensors onboard various aircraft and space platforms that were, are and will be in operation in the near future. The spectral, spatial, temporal and radiometric characteristics of these sensors have also been discussed, which may provide sufficient guidance on the selection of appropriate hyperspectral data for a particular application. A section on ground based spectroscopy has also been included where the utility of laboratory and field based sensors has been indicated. Laboratory and field measurements of spectral reflectance form an important component of understanding the nature of hyperspectral data. These measurements help in the creation of spectral libraries that may be used for calibration and validation purposes. A list of some commercially available software packages and tools has also been provided. Finally, some application areas have been identified where hyperspectral imaging may be used successfully.

An overview of basic image processing tasks that are necessary for multi and hyperspectral data analysis is given in Chap. 2. Various sections in this chapter discuss the concepts of radiometric and geometric rectification, image registration, feature extraction, image enhancement, classification, fusion and change detection operations. The objective of these sections is to briefly familiarize the reader with the role of each image processing operation in deriving useful information from the remote sensing data. Each operation has been clearly explained with the help of illustrative examples based on real image data, wherever necessary.

Part II: Theory

Having established the background on the basic concepts of data acquisition and analysis systems, Part II of the book imparts theoretical knowledge on the advanced techniques described later in this book. In this part, four chapters are included. Chapter 3 deals with the description of the mutual information (MI) similarity measure that has origins in information theory. MI is used for automatic intensity based registration of multi and hyperspectral data. As the computation of MI depends on the accurate estimation of joint histograms, two methods of joint histogram estimation have been explained. The existing joint histogram estimation methods suffer from the problem of interpolation-induced artifacts, which has been categorically highlighted and a new joint histogram estimation algorithm called generalized partial volume estimation has been proposed to reduce the effect of artifacts. Some optimization issues to maximize the MI have also been addressed.

In Chap. 4, details of a technique called independent component analysis (ICA), originally used in signal processing, have been provided. The theory of ICA discussed in this chapter forms the basis of its utilization for feature extraction and classification of hyperspectral images. ICA is a multivariate data analysis technique that commences with a linear mixture of unknown independent sources and proceeds to recover them from the original data. The merit of ICA lies in the fact that it uses higher order statistics unlike principal component analysis (PCA) that uses only second order statistics to model the data. After introducing the concept of ICA, several algorithms for determining the ICA solution have been presented, which is followed with its implementation in a couple of applications of hyperspectral data processing.

Image classification is perhaps the key image processing operation to retrieve information from remote sensing data for a particular application. The use of non-parametric classifiers has been advocated since these do not depend on data distribution assumptions. Recently, support vector machines (SVM) have been proposed for the classification of hyperspectral data. These are a relatively new generation of techniques for classification and regression problems and are based on *statistical learning theory* having its origins in *machine learning*. Chapter 5 builds the theoretical background of SVM. A section is exclusively devoted to a brief description of statistical learning theory. SVM formulations for three different cases; linearly separable and non-separable cases, and the non-linear case, have been presented. Since SVM is essentially a binary classification technique, a number of multi-class methods have also been described. Optimization, being the key to an efficient implementation of

SVM has also been given due consideration and a separate section is written to discuss the merits and demerits of existing optimization methods that have been used in SVM classification.

Chapter 6 provides the theoretical setting of Markov random field (MRF) models that have been used by statistical physicists to explain various phenomena occurring among neighboring particles because of their ability to describe local interactions between them. The concept of MRF model suits image analysis because many image properties, such as texture, depend highly on the information obtained from the intensity values of neighboring pixels, as these are known to be highly correlated. As a result of this, MRF models have been found useful in image classification, fusion and change detection applications. A section in this chapter is devoted to a detailed discussion of MRF and its equivalent form (i.e. Gibbs fields). Some approaches for the use of MRF modeling are explained. Several widely used optimization methods including simulated annealing are also introduced and discussed.

Part III: Applications

The theoretical background, concepts and knowledge introduced in the second part of the book are exploited to develop processing techniques for different applications of hyperspectral data in this part. In Chap. 7, MI based registration has been applied for automatic registration of a variety of multi and hyperspectral images at different spatial resolutions. Two different cases namely multi-sensor and multi-temporal registration, have been considered. The performance of various interpolation algorithms has been evaluated using registration consistency, which is a measure to assess the quality of registration in the absence of ground control points.

Since, the hyperspectral data are obtained in hundreds of bands, for many applications, it may be inefficient and undesirable to utilize the data from all the bands thereby increasing the computational time and cost of analysis. Hence, it may be essential to choose the most effective features that are sufficient for extracting the desired information and efficient in reducing the computational time. Chapter 8 focuses on the use of ICA for feature extraction from hyperspectral data. After clarifying the distinction between PCA and ICA, the details of two ICA based algorithms for the extraction of features have been given. The aim of these algorithms is to identify those features, which allow us to discriminate different classes that are hidden in the hyperspectral data, with high degree of accuracy. A method called spectral screening has also been proposed to increase the computational speed of the ICA based feature extraction algorithm.

In Chap. 9, the concept of ICA is further advanced to develop an ICA mixture model (ICAMM) for unsupervised classification of hyperspectral data. The advantage of using ICAMM lies in the fact that it can accurately map non-Gaussian classes unlike other conventional statistical unsupervised classification algorithms that require that the classes be Gaussian. The ICAMM finds independent components and the mixing matrix for each class using the *extended infomax learning algorithm* and computes the class membership probability for each pixel. The complete ICAMM algorithm has been explained in a simplified manner. Unsupervised classification of hyperspectral data is performed using ICAMM and its performance evaluated *vis* a *vis* the most widely used K-means algorithm.

Chapter 10 describes the application of SVM for supervised classification of multi and hyperspectral data. Several issues, which may have a bearing on the performance of SVM, have been considered. The effect of a number of kernel functions, multi class methods and optimization techniques on the accuracy and efficiency of classification has been assessed.

The two classification algorithms, unsupervised ICAMM and supervised SVM, discussed in Chaps. 9 and 10 respectively, are regarded as per pixel classifiers, as they allocate each pixel of an image to one class only. Often the images are dominated by mixed pixels, which contain more than one class. Since a mixed pixel displays a composite spectral response, which may be dissimilar to each of its component classes, the pixel may not be allocated to any of its component classes. Therefore, error is likely to occur in the classification of mixed pixels, if per pixel classification algorithms are used. Hence, sub-pixel classification methods such as fuzzy *c*-means, linear mixture modeling and artificial neural networks have been proposed in the literature. In Chap. 11, a novel method based on MRF models has been introduced for sub-pixel mapping of hyperspectral data. The method is based on an optimization algorithm whereby raw coarse resolution images are first used to generate an initial sub-pixel classification, which is then iteratively refined to accurately characterize the spatial dependence between the class proportions of the neighboring pixels. Thus, spatial relations within and between pixels are considered throughout the process of generating the sub-pixel map. The implementation of the complete algorithm is discussed and it is illustrated by means of an example

The spatial dependency concept of MRF models is further extended to change detection and image fusion applications in Chap. 12. Image change detection is one of the basic image analysis tools and is frequently used in many remote sensing applications to quantify temporal information, whereas image fusion is primarily intended to improve, enhance and highlight certain features of interest in remote sensing images for extracting useful information. Individual MRF model based algorithms for these two applications have been described and illustrated through experiments on multi and hyperspectral data.

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