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Assessment of hyperspectral MIVIS sensor capability for heterogeneous landscape classification

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ABSTRACT

The potential and limitations of the hyperspectral remote sensing MIVIS sensor (Multispectral Infrared Visible Imaging Spectrometer) in classifying heterogeneous landscapes are explored in this study. In order to quantify the discriminant information derived from selected MIVIS subsets we classified a monitored scenario by progressively increasing the feature space dimensionality. The hyperspectral subsets are defined through the Sequential Forward Selection algorithm, while mapping processes have been performed through the Maximum Likelihood, Spectral Angle Mapper and Spectral Information Divergence classifiers. Impacts of spectral bands on the overall classification accuracies and single land cover-scale reliability, as well as possible dimensionality effects (Hughes phenomenon) are investigated. The analysis is tested on a 20-km stretch of the Marecchia River (Emilia Romagna, Italy) by using MIVIS data acquired in autumn 2009 and 2010 for a 17-class mapping including complex urban/rural areas. For the considered dataset, the MIVIS sensor showed an equipment failure: of the nominal 102-band MIVIS dataset, only the first 24 bands, spanning within the 0.441–1.319 μm spectral range, were exploitable. Nevertheless, the available information provided valuable discriminant contributions in land cover mapping (Maximum Likelihood Overall Accuracy ~85%) with encouraging reliability on mixed forests, croplands, and no-vegetated floodplain patterns, whereas riparian vegetation and urban zones exhibited low classification accuracies. The relationship between the spectral space dimensionality and the minimum training-set size that is necessary to achieve a given inter-class separability has also been experimentally investigated by progressively under-sampling the original training set. The maximum under-sampling factor that avoided a decrease in the overall accuracy turned out to be, at maximum, 15 for the considered data set.

1. Introduction

Remote sensing hyperspectral sensors provide very high spectral resolution data allowing for a better discrimination among similar ground cover classes than traditional multispectral sensors (e.g., Xie et al., 2008; Xu and Gong, 2007). The hyperspectral-derived improvements are particularly important in the classification of land covers with similar spectral signatures, such as complex urban/rural landscapes (Borengasser et al., 2008). These heterogeneous patterns, including mixed environments, such as floodplain, broad-leaved and conifer forests, urban and agricultural zones, are characterized by a significant spatiotemporal variability resulting from many interconnected natural- and human- induced processes interacting in the biosphere (Forzieri and Catani, 2011). Given the large number of diverse land covers and their expected interclass spectral overlapping, hyperspectral sensors represent valuable tools for automatic detection.

Apart from the variable performances depending on the specific employed classifier (e.g., Belluco et al., 2006; Melgani and Bruzzone, 2004; Zhang et al., 2011), the main problematic issue of the analysis of hyperspectral data is related to the high dimensionality of the spectral space. First, the large number of spectral features used for classification purposes impacts on the complexity of a classifier, in terms of both computational burden and memory occupation. Furthermore, when increasing the number of features, the Hughes' phenomenon (Hughes, 1968) may occur, that consists in a loss of classification accuracy caused by the mismatch between the number of available training samples and the number of samples that should be needed to reliably estimate the classifier parameters (Landgrebe, 2003). More precisely, given a finite collection of training samples, as the number of features used for

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classification grows, the classification accuracy typically increases up to a maximum and then decreases when the number of features is further enlarged. This decaying behavior, known as the Hughes' phenomenon, occurs when the number of classifier parameters (which generally increases, often super-linearly, with the number of features) becomes so large that the fixed training set is insufficient to accurately estimate all parameters (Landgrebe, 2003). To cope with this problem, feature reduction techniques have been widely adopted and can be achieved by two main approaches, respectively based on the selection of the most informative feature subset from the original feature space (feature selection) (e.g., Cariou et al., 2011; Serpico et al., 2002), or the extraction – after a feature space transformation – of a limited number of features (feature extraction) (e.g., Benediktsson et al., 2005; Serpico and Moser, 2007). In the former case, most approaches are based on the key idea of maximizing a functional representing an inter-class distance or a separability measure. Popular choices for such a functional are the Bhattacharyya and Jeffries–Matusita distances, which are related to the error probability of a Bayesian classifier, or the divergence and normalized divergence, which rely on an information-theoretic formulation (Landgrebe, 2003; Richards and Jia, 2006). Maximizing these functionals through an exhaustive search is often computationally unfeasible for moderate to large numbers of input features (Landgrebe, 2003). Therefore, suboptimal strategies, based for instance on sequential deterministic or stochastic procedures or steepest ascent strategies, are generally used instead (Serpico et al., 2002). Concerning feature extraction through data transformation, several approaches have been proposed based on class-separability functionals, decision boundaries, nonparametric formulations, or kernel-based extensions (Landgrebe, 2003; Richards and Jia, 2006). Compared to feature-selection methods, these approaches represent more general transformations and, therefore, they can be more powerful feature reduction techniques. However, they extract a collection of transformed features that have well defined mathematical but not physical meanings. On the contrary, the output features provided by a feature selection method are a subset of the original spectral channels and consequently retain their physical meanings. A review of the feature reduction approaches for hyperspectral image classification can be found in (Serpico and Moser, 2007).

It is a shared opinion that high spatial and spectral resolution data are essential attributes to provide accurate landscape-scale mapping and/or detection results (Chanussot et al., 2006; Dell'Acqua et al., 2004). Modern space-borne hyperspectral sensors (e.g., HYPERION, CHRIS) showed increasing capabilities in land cover classification (e.g., Duca and Del Frate, 2008; Goodenough et al., 2003), but still present some inaccuracies in monitoring environments that are highly variable in space (Cavalli et al., 2008; Pignatti et al., 2009). In this context, high-resolution airborne hyperspectral sensors (e.g., AISA, MIVIS, AVIRIS, CASI, HYMAP) represent enhanced mapping tools (e.g., Gianinetto and Lechi, 2004; Lu et al., 2007; Melgani and Bruzzone, 2004) and also preliminary tests to drive planned satellite-based systems (e.g., PRISMA, EnMAP, HyspIRI). In particular, the airborne hyperspectral MIVIS sensor (Multispectral Infrared Visible Imaging Spectrometer) has been demonstrated to be a powerful instrument in land cover classifications. This sensor was developed by the Aerial Laboratory for Environmental Researches of the Italian National Research Council (LARA-CNR); it operates with high geometric and spectral resolution (depending on the flight height). MIVIS data have been used for classification purposes in many different natural contexts, such as wetland/submerged ecosystems (e.g., Belluco et al., 2006; Ciraolo et al., 2006) and mixed forests (e.g., Boschetti et al., 2007; Pignatti et al., 2009). Results showed the great potential of the MIVIS sensor in identifying terrestrial vegetation species, such as pine, oak, willow, poplar and alder (Boschetti et al., 2007). MIVIS data have been also successfully exploited for retrieving the complex urban tissue (Cavalli et al., 2008) by distinguishing the main anthropogenic surfaces (e.g. roofing and paving materials). In light of these encouraging performances, additional experiments on heterogeneous urban/rural landscapes could provide a better understanding of the MIVIS strengths and limitations on classification tasks.

In order to explore the potential of MIVIS for land-cover discrimination, in this paper we tested its discriminant contribution to classify complex environments including diverse forest species, riparian vegetation, cropfield, and urban infrastructures (17-class set). For this purpose we used different supervised classifiers and hyperspectral subsets identified through a feature selection approach. Land cover-based performances and possible hyperspectral-derived dimensionality effects are analyzed. The main novel contribution of this paper is the experimental investigation of the MIVIS sensor capability for classification purposes of landscapes with heterogeneous land covers.

2. Methods

2.1. Study area

The study was conducted on a 20-km stretch of the Marecchia river ($\sim$40 km^2), that sources in Eastern Tuscany and runs at the border of the regions of Emilia-Romagna and Marche, in North-Eastern Italy (43°N, 12°E), (Fig. 1). Such study area has been chosen for its complexity in land cover spatial variability, prevalently controlled by climatic and lithologic factors (Mannori and Sani, 1987; PAI-Hydrological planning, 2004), and represents an excellent test to quantify the hyperspectral remote sensing capability in classification problems of heterogeneous landscapes. The hill slopes are characterized by a significant biodiversity of arboreal species, which include conifer and broad-leaved types, such as oak, pine, cypressus and spruce (Fig. 1A, mixed forest). Riparian ecosystems show complex patterns with flexible and stiff vegetation in different evolutionary stages, such as willow, arundo donax, heatland and poplar (Fig. 1B, floodplain). The valley floor is prevalently made up of fabrics alternated with industrial units and connected through dense asphalt road network and gardens (Fig. 1C, urban zone), agricultural fields, such as croplands and olive groves, and semi-natural vegetation, such as meadows (Fig. 1D, agricultural area).

We defined 17 main target land cover classes to discriminate in the classification process: water river (WR), water lagoon (WL), bare soil (BS), asphalt (AS), plowed field (PF), urban fabric (UF), industrial unit (IU), herbaceous (HE), heatland (HL), arundo donax (AD), poplar (PL), oak (OK), pine (PN), cypressus (CY), spruce (SP), willow (WI), and olive (OV). The afore-mentioned land cover classes have been selected to assess the MIVIS potential for classification tasks in diverse application fields such as urban planning, river restoration, agricultural and forestry resource management.

2.2. Remote sensing and field data

Hyperspectral data were collected in two different acquisition times in December 6, 2009 and October 23, 2010 within a time-frame spanning from 10.00 to 14.00 UTC, through the MIVIS sensor, which is a whiskbroom sensor with high spatial (3 $\times$ 3 m pixel size), spectral (0.02 μm and 0.05 μm for the first and second spectrometer, respectively) and radiometric (12 bit) resolution. Each MIVIS image set covers the whole study area and counts 102 bands distributed within the visible and infrared regions of the spectrum between 0.43 and 12.7 μm. Color-infrared ADS40 images (0.2-m spatial resolution) and Light Detection and Ranging (LiDAR) data