Use of FPGA or GPU-based architectures for remotely sensed hyperspectral image processing

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Abstract

Hyperspectral imaging is a growing area in remote sensing in which an imaging spectrometer collects hundreds of images (at different wavelength channels) for the same area on the surface of the Earth. Hyperspectral images are extremely high-dimensional, and require advanced on-board processing algorithms able to satisfy near real-time constraints in applications such as wildland fire monitoring, mapping of oil spills and chemical contamination, etc. One of the most widely used techniques for analyzing hyperspectral images is spectral unmixing, which allows for sub-pixel data characterization. This is particularly important since the available spatial resolution in hyperspectral images is typically of several meters, and therefore it is reasonable to assume that several spectrally pure substances (called endmembers in hyperspectral imaging terminology) can be found within each imaged pixel. In this paper we explore the role of hardware accelerators in hyperspectral remote sensing missions and further inter-compare two types of solutions: field programmable gate arrays (FPGAs) and graphics processing units (GPUs). A full spectral unmixing chain is implemented and tested in this work, using both types of accelerators, in the context of a real hyperspectral mapping application using hyperspectral data collected by NASA’s Airborne Visible Infra-Red Imaging Spectrometer (AVIRIS). The paper provides a thoughtful perspective on the potential and emerging challenges of applying these types of accelerators in hyperspectral remote sensing missions, indicating that the reconfigurability of FPGA systems (on the one hand) and the low cost of GPU systems (on the other) open many innovative perspectives toward fast on-board and on-the-ground processing of remotely sensed hyperspectral images.

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1. Introduction

Hyperspectral imaging is concerned with the measurement, analysis, and interpretation of spectra acquired from a given scene (or specific object) at a short, medium or long distance by an airborne or satellite sensor [1]. The wealth of spectral information available from latest-generation hyperspectral imaging instruments, which have substantially increased their spatial, spectral and temporal resolutions, has quickly introduced new challenges in the analysis and interpretation of hyperspectral data sets. For instance, the NASA Jet Propulsion Laboratory’s Airborne Visible Infra-Red Imaging Spectrometer (AVIRIS) [2] is now able to record the visible and near-infrared spectrum (wavelength region from 0.4 to 2.5 μm) of the reflected light of an area 2–12 km wide and several kilometers long using 224 spectral bands. The resulting data cube (see Fig. 1) is a stack of images in which each pixel (vector) has an associated spectral signature or ‘fingerprint’ that uniquely characterizes the underlying objects, and the resulting data volume typically comprises several Gigabytes per flight. This often leads to the requirement of hardware accelerators to speed-up computations, in particular, in analysis scenarios with real-time constraints in which on-board processing is generally required [3]. It is expected that, in future years, hyperspectral sensors will continue increasing their spatial, spectral and temporal resolutions (images with thousands of spectral bands are currently in operation or under development). Such wealth of information has opened groundbreaking perspectives in several applications [4] (many of which with real-time processing requirements) such as environmental modeling and assessment for Earth-based and atmospheric studies, risk/hazard prevention and response including wild land fire tracking, biological threat detection, monitoring of oil spills and other types of spillage.

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of chemical contamination, target detection for military and defense/security purposes, urban planning and management studies, etc. [5].

Even though hyperspectral image processing algorithms generally map quite nicely to parallel systems such as clusters or networks of computers [6,7], these systems are generally expensive and difficult to adapt to on-board data processing scenarios, in which low-weight and low-power integrated components are essential to reduce mission payload and obtain analysis results in real-time, i.e. at the same time as the data is collected by the sensor [3]. Enabling on-board data processing introduces many advantages, such as the possibility to reduce the data down-link bandwidth requirements by both pre-processing data and selecting data to be transmitted based upon some predetermined content-based criteria [8]. In this regard, an exciting new development in the field of commodity computing is the emergence of programmable hardware accelerators such as field programmable gate arrays (FPGAs) [9] and graphic processing units (GPUs) [10], which can bridge the gap toward on-board and real-time analysis of hyperspectral data [8,11].

The appealing perspectives introduced by hardware accelerators such as FPGAs (on-the-fly reconfigurability [12] and software-hardware co-design [13]) and GPUs (very high performance at low cost [14]) also introduce significant advantages with regards to more traditional cluster-based systems. First and foremost, a cluster occupies much more space than an FPGA or a GPU. This aspect significantly limits the exploitation of cluster-based systems in on-board processing scenarios, in which the weight (and the power consumption) of processing hardware must be limited in order to satisfy mission payload requirements [3]. On the other hand, the maintenance of a large cluster represents a major investment in terms of time and finance. Although a cluster is a relatively inexpensive parallel architecture, the cost of maintaining a cluster can increase significantly with the number of nodes [6]. Quite opposite, FPGAs and GPUs are characterized by their low weight and size, and by their capacity to provide similar computing performance at lower costs in the context of hyperspectral imaging applications [11,12,14–18]. In addition, FPGAs offer the appealing possibility of adaptively selecting a hyperspectral processing algorithm to be applied (out of a pool of available algorithms) from a control station on Earth. This feature is possible thanks to the inherent re-configurability of FPGA devices [9], which are generally more expensive than GPU devices [14]. In this regard, the adaptivity of FPGA systems for on-board operation, as well as the low cost and portability of GPU systems, open innovative perspectives.

In this paper, we discuss the role of FPGAs and GPUs in the task of accelerating hyperspectral imaging computations. A full spectral unmixing chain is used as a case study throughout the paper and implemented using both types of accelerators in a real hyperspectral application (extraction of geological features at the Cuprite mining district in Nevada, USA) using hyperspectral data collected by AVIRIS. The remainder of the paper is organized as follows. Section 2 describes a hyperspectral processing chain based on spectral unmixing, a widely used technique to analyze hyperspectral data [8,11].

2. Hyperspectral unmixing chain

In this section, we present spectral unmixing [19] as a hyperspectral image processing case study. No matter the spatial resolution, the spectral signatures collected in natural environments are invariably a mixture of the signatures of the various materials found within the spatial extent of the ground instantaneous field view of the imaging instrument [20]. The availability of hyperspectral instruments with a number of spectral bands that exceeds the number of spectral mixture components allow us to approach this problem as follows. Given a set of spectral vectors acquired from a given area, spectral unmixing aims at inferring the pure spectral signatures, called endmembers [21,22], and the material fractions, called fractional abundances [23], at each pixel. Let us assume that a
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