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HYPERSPECTRAL IMAGE PROCESSING PIPELINES ON MULTIPLE PLATFORMS FOR COORDINATED OCEANOGRAPHIC OBSERVATION

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ABSTRACT

The large size of hyperspectral images and the computational demands required for interpreting them complicates their acquisition, distribution, and utilization by remote agents. The Norwegian University of Science and Technology is building an ocean observation system, including the HYPSO-1 hyperspectral imaging satellite, to monitor ocean color in coastal waters. The images collected by HYPSO-1 will be used to inform an ensemble of robotic agents which locally monitor ocean conditions. Several agents will be unmanned aerial vehicles that likewise carry hyperspectral imagers. Hyperspectral images will be processed on-board the different agents, as well as on the ground. Here, we discuss the architecture, development, current status, and future opportunities of hyperspectral image processing pipelines on these platforms.

***Index Terms*—** Autonomous systems, embedded systems

1. INTRODUCTION

The ocean is critical to the welfare of humankind. However, it is also sensitive to climate change and is largely unexplored relative to earth's continents [1]. Improved monitoring is necessary for maintaining a healthy relationship between humans and the ocean. One key signature of ocean health is its color, which is suitable for being measured by remote sensing [2]. By recording more wavelengths of light, hyperspectral imaging can reveal characteristic signatures of ocean phenomena such as oil spills, algal blooms, and plastics [3, 4]. Much work has focused on on-board processing of hyperspectral images on both unmanned aerial vehicles (UAVs) and satellites [5, 6, 7].

This proceeding describes hyperspectral image processing pipelines (HIPPs) developed for the HYPSO-1 satellite and UAVs, as well as additional capabilities which have been developed on the ground to facilitate their operation. Each platform has its own purpose and constraints that guide the design and development plan of each HIPP. The different platforms come together in the Mission-oriented Autonomous systems with Small Satellites for marItime sensing, surVEillance and communication (MASSIVE) project at the Norwegian University of Science and Technology. The project consists of a series of small satellites, the first of which is the HYPerspectral Smallsat for Ocean observation (HYPSO-1) [8], combined with an ensemble of robotic agents, including both UAVs and the AutoNaut, an autonomous surface vehicle which can be used to validate ocean color observations and relate ocean color to local conditions [9] (Fig. 1). The acquired data are processed on the ground at the mission control center, before being dispersed to end-users. This proceeding discusses how hyperspectral imaging is being integrated into a multi-agent system, and will describe the image processing tools that are being built to facilitate its use.

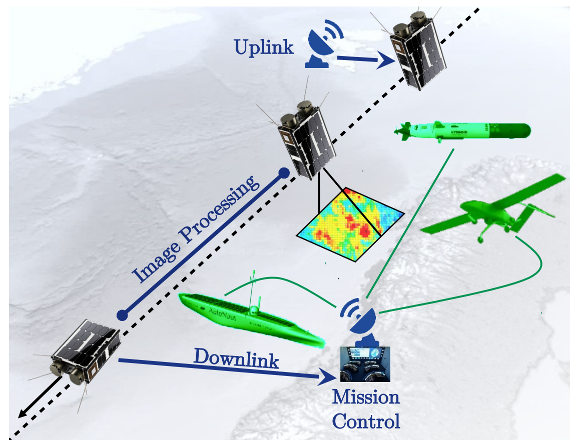

Fig. 1. The hyperspectral observations of the HYPSO-1 satellite will inform an ensemble of *in situ* autonomous agents.

Purpose of each pipeline The HYPSO-1 satellite will image ocean color, over a region of about 5000 km^2, with about

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Table 1. Modules considered for the pipelines

Module	Purpose
Acquisition	To collect spectrograms
Compression	To reduce size
Sensor cor.	To eliminate systematic errors
Image registration	To place pixels on a grid
Georeferencing	To position the data on earth
Super-resolution	To emphasize spatial information
Atmospheric cor.	To mitigate atmospheric effects
Dim. reduction	To extract crucial information
Target detection	To locate target spectra
Classification	To partition image using spectra

100 evenly spaced bands in the 400 – 800 nm range. As a small satellite in low earth orbit with a revisit time of approximately 90 minutes, it will be able to point towards algal bloom events and image their dynamic evolution up to three times a day. HYPSO-1 will use S-band radio, which enables downlink speeds of about 1 Mb/s.

A primary goal of image processing on-board the satellite is to reduce the size of the data, while retaining as much useful information as possible. Because the expected size of the raw data is a few hundred MB, it will take several passes to be downlinked in its raw form, but its size can be reduced by on-board processing. There are three tactics for utilizing the downlinked data: either it can (1) be processed further on the ground and transmitted to autonomous agents, (2) processed on the ground for storage in a repository, or (3) transmitted to the autonomous agents without further processing.

Unmanned aerial vehicles (UAVs) will both supplement the satellite observations and image ocean phenomena independently. During cloudy conditions when HYPSO-1 cannot observe, they will be used to image under the clouds. In better weather conditions, they will acquire images at greater spatial resolution and better signal-to-noise ratio (SNR) than what is possible with HYPSO-1, to calibrate the satellite's hyperspectral camera with simultaneous nadir overpass [10], and to sample regions at higher temporal resolution for the purposes of data assimilation. The primary goal of the HIPPs on UAVs is to reduce size of information so that it can be stored on-board with minimal information loss because it can be physically transferred to the operator, unlike data on the satellite. The hyperspectral images collected by the drone could also be used by its navigational system to perform adaptive sampling such as circling the perimeter of an algae bloom [11]. Although the UAVs may be carrying different models of cameras than the satellite, many of the image processing modules can and will be reused.

The purpose of the analysis capabilities developed for use on the ground is to aid the UAVs and satellites in their mission. For example, for the data to be interepretable, it is necessary to know what the wavelength each column in a spectrogram corresponds to. Before a flight, the radiometric, spectral, and spatial properties of the response of the camera are calibrated and parameters are determined to convert data into the desired format [12]. Applying this calibration, to the data on-board the agents as it is collected can standardize it and eliminate undesired systematic effects before further on-board processing. The ground pipeline is used to parametrize the characteristics of the hyperspectral camera, which then can be applied on-board the remote platforms. In addition, the ground HIPPs will also be used to coordinate the satellites and other agents. For example, the satellite data can be used to determine where the *in-situ* agents should go.

Constraints These pipelines are being developed to support hyperspectral imagers similar to the one described in Sigernes *et al.* [13]. Different variants of the camera are being produced for use on either the satellite or UAV, but their core design and operation remain similar.

The computational hardware differs between the platforms. The satellite uses a system-on-a-chip with a customized carrier board, which can utilize an on-chip field programmable gate array (FPGA) for low-power accelerated computations (Fig. 2). On the other hand, the two UAV imaging payloads lack FPGA acceleration, but do include GPUs. One version of the UAV payload is oriented towards tagging the acquired spectrograms with time and pose, whereas the other is designed to enable users to operate the system simply. The ground analysis software is designed to be run on a laptop, so that it can be used while operating UAVs, or a desktop, to be run at the HYPSO-1 Mission Control Center.

Because of differing choices for the computational hardware, the algorithms utilizing either FPGA or GPU acceleration cannot be run natively on both systems. This imposes a high cost for developing in parallel for these systems. Therefore, algorithms are tested as part of a pipeline on the ground, where more computational resources are available, before being developed for the other systems. For both the satellite and the UAVs, there is also a time constraint on the computation. Either the data must be processed as they are collected or the agent must alternate between imaging and processing.

2. DESIGN AND DEVELOPMENT

Satellite The HYPSO-1 satellite will image a region of the ocean for about one minute and process the acquired data for at most three minutes more [8]. From its conception, the HYPSO-1 satellite on-board processing pipeline was planned to incorporate the image processing modules listed in Table 1. Several image processing pipelines, each containing a subset of the modules, are in development, with each designed to produce a particular data product.

The HSI camera, an RGB camera (UI-1252LE), and the on-board processing unit (OPU) together form the payload of the satellite. The OPU consists of a Zynq 7030 System-on-Chip (Xilinx) together with a custom carrier board (Fig. 2). The HIPP runs on an embedded Linux operating system,

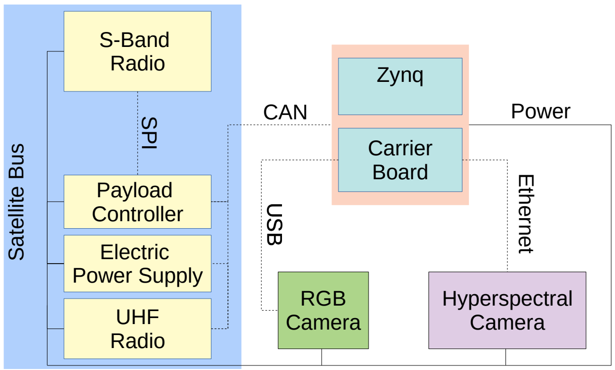

Fig. 2. The camera payload on the satellite included the hyperspectral imager, an on-board processing unit, and an RGB camera. The blue highlighted regions show the subsystems of the spacecraft that the payload interacts with. Power is supplied over the solid lines, while data is transmitted over the dashed lines. Note that only subsystems involved in data acquisition, processing, and downlinking are pictured.

and the modules are partitioned between CPU and FPGA, and therefore written in either C or VHDL. Interfaces facing the FPGA are implemented using Linux kernel modules. A Linux based operating system is used (as opposed to a real time operating system or a bare metal solution), due to proprietary software needed to interface with the COTS camera module used in the hyperspectral imager. The cubeDMA interface is used to facilitate flexible communication of the hyperspectral data structures between memory and FPGA [14].

The compression and dimensionality reduction modules are prioritized because they directly reduce the size of the data and can be utilized in more configurations of the HIPP. The simplest of the configurations for the satellite, which we call the minimal pipeline, consists of image acquisition, compression, and downlinking (Fig. 3). The compression module follows the CCSDS-123 standard and is implemented in the programmable logic [15, 16]. An alternate version of the compression code which runs on the CPU can also be run, in case some aspect of the FPGA fails to operate as expected in space. However, the CPU version takes about 30× longer to process, so the FPGA implementation is preferred for operational reasons. Sensor corrections, such as compensation for smile and keystone, are prioritized next. The next configuration builds on the first, but also adds smile and keystone sensor corrections [12] and dimensionality reduction (DR) [17] to the pipeline. The smile and keystone corrections are included because DR removes information that is necessary to correct for smile and keystone, which preclude applying the corrections after the DR data are downlinked. It is possible to change the number of components which are selected from DR in order to meet the memory requirements of a certain rate of downlink. The standard plan is to downlink the 20 bands which are most important to reconstructing the image, which will reduce the size of the data package by about 5×. The pipeline that adds both the a smile and keystone correction and the DR is the baseline (Fig. 3). Other modules that have been prototyped on the ground for incorporation into the satellite HIPP include super-resolution and target detection [18, 19, 20].

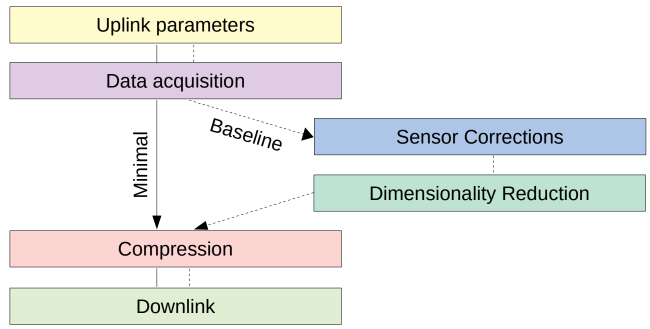

Fig. 3. The minimal on-board image processing pipeline provides the basic structure that all more sophisticated pipelines will build on. The baseline on-board image processing pipeline adds dimensionality reduction to increase the speed at which the data can be downlinked.

UAV In order to have a simple way to mount the hyperspectral imager on a variety of drones, several different payloads have been developed to acquire and process images. The original payload, called the Lunde, was developed for mounting the camera on UAVs and acquiring images [21]. Because different users of the camera had different demands, two new versions of the payload have been designed.

The first payload consists of a processor (Odroid XU-4, Hardkernel) together with a voltage converter, a 1 TB solid state drive (PNY), and an ethernet connection to the drone (Figs. 4 and 5). This payload is designed to complement the accessibility of the do-it-yourself camera [13] because it is composed of relatively cheap commercially available components. The Odroid controls the camera through the DUNE Unified Navigational Environment [22], which in turn controls the uEye (IDS) camera driver. In order to make the payload easy to use, imaging automatically begins when the Odroid is powered on. The acquired data can then be accessed directly through the hard drive so that there is no need for the operator to modify the payload. For more flexibility, however, the camera can also be controlled remotely, though the DUNE software.

The second payload is designed for more precise scientific measurements. It is based on the Jetson TX2 processor (Nvidia) and follows the same basic configuration of the first payload, but adds an IMU (Analog Devices Inc. ADIS 16490 BMLZ) and a GNSS system (module: u-blox Neo-M8T, antenna: Harxon HX-CH3602A). A reconfigurable timing board (SenTiBoard) is used to synchronize and align the timing information of the camera with the pose [23]. Knowing the pose of the UAV is critical for determining the geophysical locations from which hyperspectral pixels originate.

Some camera operators have wanted to fly the camera without an additional computing payload, in order to reduce size and weight. To facilitate this, a python script based on the pypyueye library is used to control the camera [24]. While this lacks the precise timing information and remote control through DUNE, it requires less additional software to be installed. A secondary benefit that we have encountered is that this implementation is straight-forward to integrate with modules developed from other organizations into the pipeline, due to the ubiquitousness of python. For example, the smile and keystone correction developed and tested for the ground pipeline can be run directly without alteration in this version of the pipeline.

Ground HIPPs are used to develop and test modules to be run on the UAV. For example, in the classification task, the spectra of relevant classes are determined on the ground are evaluated on an example data sets before being run in the field. Off-line analysis of the Hyperspectral Imager of the Coastal Ocean [25] suggest that the classification technique described in [17] is sufficient to distinguish between different constituents such as chlorophyll and pollution. Experiments are currently being prepared to test the performance of classification while the drone is flying.

3. CONCLUSIONS

Here we have presented the purposes, constraints, design choices, and development progress of several hyperspectral imaging systems and processing pipelines. These systems will be united in the MASSIVE ocean observation project. The version of the HIPP that will be on the HYPSO-1 when it launches has been finalized. Changes to that pipeline must either rely on the in-flight update capacity of the satellite or wait to be implemented on the next satellite in the constellation. Because it is simpler to collect data from UAVs than from satellites, the development of their HIPPs has been somewhat slower and more attention has been focused on ease of use and tailoring the payloads to different use-cases. For example, the UAV payloads can be augmented with an RGB camera to investigate joint hyperspectral-multispectral imaging strategies, both for their own utility and to investigate how they might be incorporated on the satellite [26]. Still, as the UAVs become more autonomous and fly longer missions, the computational capacity of their HIPPs will become more important.

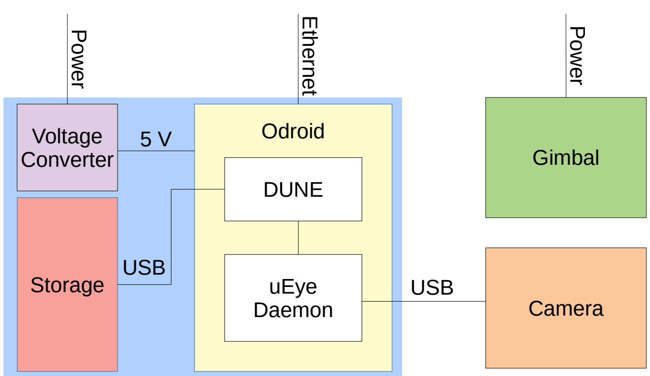

Fig. 4. The hyperspectral camera UAV payload is based on an Odroid which runs DUNE which in turn controls the uEye daemon to operate the camera.

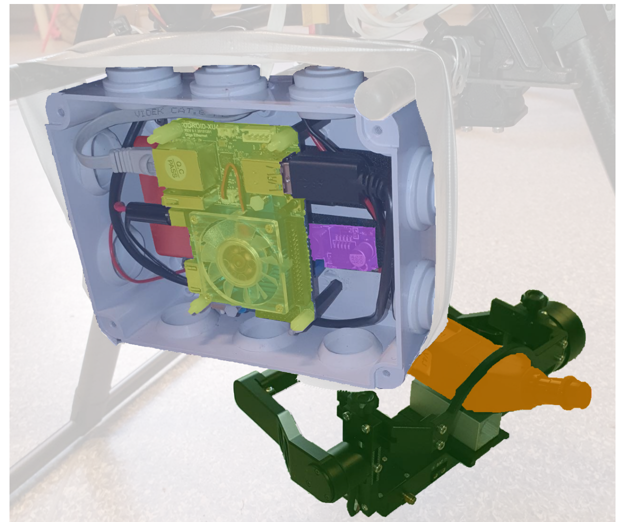

Fig. 5. The UAV hyperspectral payload mounted on a multiroter. Note that the the components are colored in order to correspond to Fig. 4.

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