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Compressive Sensing instrumental concepts for space applications

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ABSTRACT

The need of high-resolution Earth Observation (EO) images for scientific and commercial exploitation has led to the generation of an increasing amount of data with a material impact on the resources needed to handle data on board of satellites. In this respect, Compressive Sensing (CS) can offer interesting features in terms of native compression, on-board processing and instrumental architecture. In CS instruments the data are acquired natively compressed by leveraging on the concept of sparsity, while on-board processing is offered at low computational cost by information extraction directly from CS data. In addition, instrument's architecture can enjoy super-resolution capabilities that ensure a higher number of pixels in the reconstructed image with respect to that natively provided by the detector. In this paper, we present the working principle and main features of a CS demonstrator of a super-resolved instrument for EO applications with ten channels in the visible and two channels in the medium infrared. Besides the feature of merging in a single step the acquisition and compression phases of the image generation, its architecture allows to reach a super-resolution factor of at least 4x4 in the images reconstructed at the end of process. The outcome of the research can open the way to the development of a novel class of EO instruments with improved Ground Sampling Distance (GSD) - with respect to that one provided natively by the number of sensing elements of the detector - and impact EO applications thanks to native compression, on-board processing capabilities and increased GSD.

Keywords: Compressive Sensing, Spatial Light Modulator, Digital Micromirror Device, Earth Observation, Medium Infrared, spectroradiometer

1. INTRODUCTION

Earth Observation (EO) data has become ever more vital to our understanding of our planet, to monitor risks and to help society at large with the provision of successful public services and private initiatives. Applications include mapping and characterization of the Earth for planning and monitoring of the territory and the environment, from monitoring of natural and anthropogenic risks (e.g. pollution, floods, desertification, fires), to services to marine and agro-forestry sectors. EO from space has many benefits compared to other observation means (e.g. aerial), in particular its low operation cost and large availability.

The pursuit of high-quality data for scientific and commercial exploitation, however, has fostered the need of high-resolution EO images, which - also thanks to the evolution of acquisition technologies - has led to the generation of an increasing amount of data with a material impact on the EO instrument's requirements in terms of on-board computation, memory resources and datalink bandwidth. Payload's resources must in fact guarantee the handling of very high data rates with limited power consumption, while the transmission system can become a bottleneck that prevents full exploitation of the acquired information.

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In this context, Compressive Sensing (CS) paradigm can mitigate these issues performing acquisition of natively compressed data and information extraction from the acquired data and images directly onboard satellites. Information extraction prior to the reconstruction of the images, in fact, can open the way to a screening and selection of the acquired images in order to generate early-warning alarms with very low latency, bypassing the image transmission and processing chain.

Besides the advantages provided in terms of signal processing and on-board resource requirements, a fascinating feature offered by the CS is the capability of enabling novel instrumental concepts for EO imagers, in which the CS architecture implemented by means of a Spatial Light Modulator (SLM) placed at the image plane of the fore-optics, is used to provide super-resolution features to the instrument. The concept of super-resolution refers to the possibility of obtaining a final image with a higher number of pixels than the nominal number of sensing elements of the detector used: this is obtained thanks to the use of an SLM – placed at the image plane - with a number of elements NxN times greater than the elements of the detector. A single pixel on the detector is associated with each NxN group of SLM elements. The image focused on the SLM is modulated through appropriate binary coding masks. Each pixel of the detector thus integrates the light coming from a group of NxN elements. The samples acquired make it possible to obtain - by means of suitable reconstruction algorithms - an image having the same number of pixels as that on the image plane at the SLM. If NxN modulations are performed during the acquisition, there is no data compression; but if the number of modulations is lower yet sufficient for the reconstruction of the image thanks to the signal sparsity, an intrinsic compression is obtained (CS paradigm).

A typical example of CS instrumentation is the single-pixel camera, first developed at the Rice University, Texas [1]. In the single pixel camera, a single photodetector is used instead of a 2D detector in order to implement an imaging system. This feature can assume an interesting role in those spectral regions – like the infrared (IR) spectral range – in which single element detectors are more easily available at a reasonable cost or have better performances with respect to detector arrays/matrices. Architectural-wise, CS technique in space applications can provide other advantages in terms of payload budgets since the compression board is not needed any longer and downlink requirements are less stringent.

In the last decade, there has been an increasing interest to explore the potential of CS also for space applications. Actually, most CS instruments in the literature have mainly addressed spectroscopic applications [1][2][3], while only very few have devoted to space applications [4][5][6]. Following an Innovation Triangular Initiative (ESA ITI-A SATSAMP project for software proof-of-concept of compressive hyperspectral imaging and ESA ITI-B HPSI project on Hyperspectral Passive Satellite Imaging via compressive sensing) funded by the European Space Agency (ESA), the latter has funded two competitive projects on Optical CS Technologies for Space Applications (ESA contract on Optical Compressive Sensing Technologies For Space Applications (CS4Space) and ESA contract on Optical Compressive Sensing Technologies For Space Applications (OCS-TECH)). Both studies focused on exploring the potential of CS-based optical instrumentation for space applications and to demonstrate the existence of substantial advantages - with respect to a traditional system - in terms of the resources required for its development. The projects were not limited to investigate Earth Observation (EO) application domain, but also explored potential benefits for Space Science (SS) and Planetary Exploration (PE) [7],[8],[9]. Recently, the Italian Space Agency (ASI) has also funded the SISSI project for a feasibility study of a super-resolved compressive sensing multispectral imager in the medium infrared [10][11].

At the same time, space agencies have started to fund environmental tests in order to mature the Technological Readiness Level (TRL) of key components like SLM. Both ESA and NASA have carried out space-qualification tests on some models of Digital Micromirror Device (DMD) manufactured by Texas Instrument company. As part of the EUCLID mission, ESA had funded a series of environmental tests (vibrational, thermo-vacuum, rad-hardness) for the qualification of a DMD model (matrix of 2048 x 1080 micromirrors with a pitch of 13.68 μm) produced by Texas Instrument [12]. On the other hand, NASA, together with the Rochester Institute of Technology and Johns Hopkins University, have carried out a detailed study for the spatial qualification of the Texas Instrument's DMD DLP®7000 model [13].

In this paper, we present the working principle and main features of a demonstrator of a super-resolved CS instrument for EO applications with ten channels in the visible Near InfraRed (VNIR) and two channels in the Medium InfraRed (MIR) spectral regions. The demonstrator is being developed in the frame of a recently EU H2020-funded project on a super-resolved compressive instrumentation - in the visible and medium infrared - for EO applications (the SURPRISE project). Besides the feature of merging in a single step the acquisition and compression phases of the image, its architecture allows to reach a super-resolution factor of at least 4x4 in the images reconstructed at the end of process. The outcome of the research can open the way to the development of a novel class of EO instruments with improved

Ground Sampling Distance (GSD) - with respect to that one provided natively by the number of sensing elements of the detector - and impact EO applications thanks to native compression, on-board processing capabilities and increased GSD.

2. COMPRESSIVE SENSING

CS relies on two main concepts: sparsity and incoherence [14][15]. A signal is said to be sparse when most of its components are equal to zero. In particular a signal is *"k-sparse"* if it has - at most - *k* non-zero entries. In a real case scenario, however, signals are often sparse in a domain different from the original one, so that x will be considered sparse also if it has a sparse representation in some basis. The sensing process of CS thus relies on the assumption that the signal *x* is "sparse" in some domain. Incoherence instead refers to the requirement that the sensing matrix, unlike the signal (image) of interest, should have a very dense representation in the representation basis. In this case, nonlinear reconstruction algorithms can recover the signal (image) with high fidelity.

In other words, the main idea of CS is that, thanks to prior knowledge about the signal's sparsity and by using a suitable sensing matrix, the signal can be reconstructed using fewer samples than those dictated by the Shannon-Nyquist theorem. Thus, in a typical approach to signal compression, data is first sampled and then compressed to reduce final amount of data to handle, whereas in CS approach the volume of acquired data is directly reduced during the acquisition phase.

From a practical point of view, CS is implemented through the acquisition of a set of spatially integrated measurements of the image to be acquired, modulated by a suitable spatially-coded pattern (sensing matrix) that is applied to the image by means of an SLM. The latter is the device that physically performs the scalar product between a random pattern (sensing matrix) and the image. A suitable optical system (condenser) is finally used to integrate the coded image and focus it on a single-pixel detector that acquires measurements. Image reconstruction is performed by determining the sparsest signal that matches the series of integrated measurements that were acquired. This last step can be performed by using linear programming techniques [16] or greedy optimization algorithms. Recently, also deep learning methods have successfully been applied to CS reconstruction problem [17]. It is worth noting that, in the case of space applications, the image reconstruction is performed at the ground segment.

3. THE SURPRISE DEMONSTRATOR

The SURPRISE's demonstrator implements an instrumental concept based on a CS architecture. The aim of the demonstrator is to show how the use of Spatial Light Modulation (SLM) technology and Compressive Sensing (CS) can be exploited to yield a significant improvement of the performance of EO super-spectral payloads in the visible (VIS), near- (NIR) and medium-wave infrared (MIR) spectral regions, with an emphasis on their Ground Sampling Distance (GSD), on-board data processing and data encryption capabilities.

The SURPRISE demonstrator is based on a CS-based architecture that uses a SLM as modulating device to demonstrate the feasibility of a super-resolved compressive instrument providing advantages for the development of an EO payload in the VIS-NIR and MIR. Although the specifications of the SURPRISE demonstrator - in terms of number of spectral channels, radiometric accuracy, fore-optics, etc. - are necessarily simplified with respect to those of a counterpart EO payload, its design is conceived to be scalable to a more challenging – and expensive - implementation of an EO payload.

3.1 Working principle

The instrument's working principle is based on the use of an SLM - specifically a Digital Micromirror Device (DMD) - as a core element in order to increase the number of pixels in the reconstructed image with respect to that guaranteed by the number of pixels of the detector. The acquisition of a series of measurements – each of which corresponds to the integrated value of the image modulated by an SLM pattern - is used to reconstruct the super-resolved image with a number of pixels that is higher with respect to the ones provided natively by the elements of the detector. If we use a set of suitable modulation patterns on the SLM and apply the CS paradigm, the image can be reconstructed by acquiring a number of measurements smaller than the number of pixels of the reconstructed image.

Since by using the CS concept we use a single detector to acquire information about N x N micropixels (where N x N detectors would be needed by a conventional imaging method) CS is said to provide a super-resolution (SR) factor. The SR factor is thus defined as the ratio between the number of micropixels and the number of detectors:

$$SR\,factor = \frac{N\ x\ N}{\#\ of\ DETECTORS} \quad . \tag{1}$$

Figure 1 illustrates the working principle of the SURPRISE demonstrator. A generic target is imaged by a collection optics. The image (hereinafter referred to as 'macropixel') is focused on an SLM providing spatial coding of the target with a higher number of pixels. Such spatially coded image is then spatially integrated (averaged) by a condenser lens and acquired by a single-pixel sensor. The acquisition is iterated by using a sequence of spatial coding masks. If the number of pixels granted by the SLM is N x N (each of which hereinafter referred to as 'micropixel'), a linearly independent sequence of N x N spatially coded acquisitions allows the reconstruction of the macropixel super-resolved into N x N micropixels.

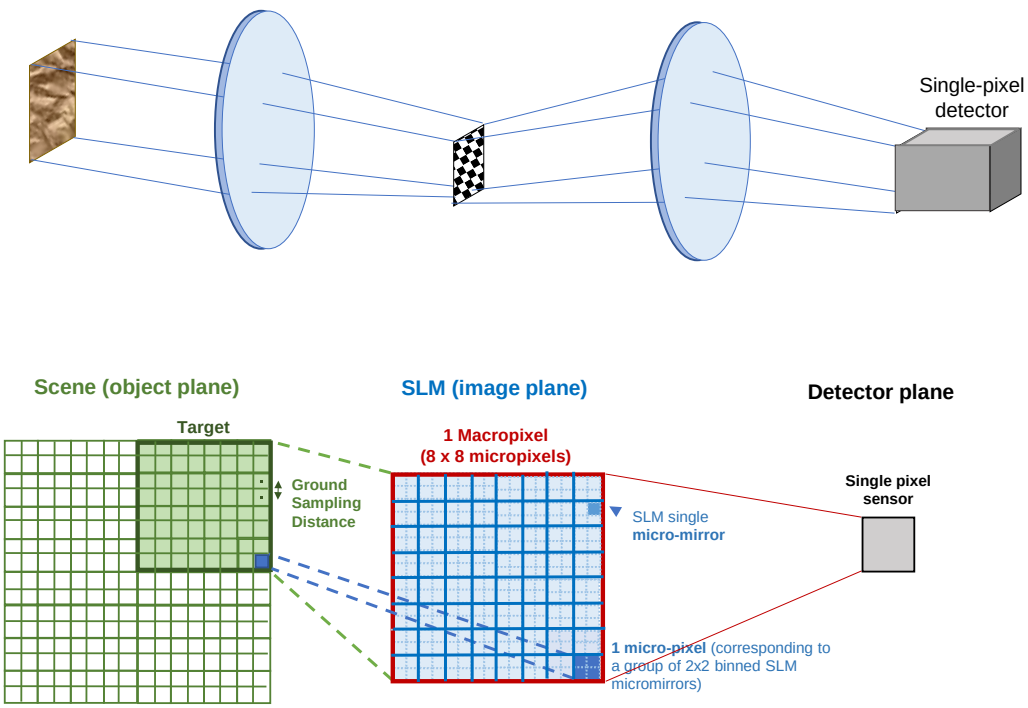

Figure 1. Working principle of the SURPRISE demonstrator.

Each micropixel can be made of a single micromirror of the SLM or a group of binned micromirrors, where binned indicates that the micromirrors are actuated all in the same way/state. By applying CS theory, the number of acquisitions for the reconstruction of the super-resolved macropixel (N x N acquisitions) can be reduced, obtaining a N x N super-resolved reconstructed image (lossy compression). The loss of information depends on the sparsity of the scene in the compressed domain (defined by the spatial coding sequence) and on the compression ratio.

Figure 1 (bottom) reports an example, in which the target is imaged on an SLM area made of 16 x 16 micromirrors. This area corresponds to one macropixel. In this example, each macropixel is made of 8x8 micropixels. On turn, each micropixel is made of 2x2 micromirrors that are acted as a single virtual mirror (binned micromirrors). It is important to

note that each micropixel conveys information about a given spatial area of the target and that the distance between the centers of two adjacent micropixels on the SLM corresponds to the Ground Sampling Distance (GSD) on the target. Thus, the GSD is determined by the amount of micromirror binning performed. Depending on the amount of binning performed, the size of the micropixel changes, and accordingly the GSD on the target. In this case, the SR factor, given by the ratio between the number of micropixels and the number of detectors, is equal to 8 x 8.

3.2 Overall architecture

The SURPRISE demonstrator is conceived as a whiskbroom spectral imager that operates in two different spectral regions, the VIS-NIR and the MIR, with ten channels in the VIS-NIR and two channels in the MIR. Figure 2 shows a block diagram of the demonstrator's architecture, with detail of the optical unit. The three main subsystems of the demonstrator are:

- Target Scanning System, that is used to scan the scene and to mimic a whiskbroom operation;
- Master Unit, that guarantees proper synchronization of all sensors and actuators, and that provides data handling;
- Optical Unit, which constitutes the CS instrument's core section with the SLM acting as a coding mask.

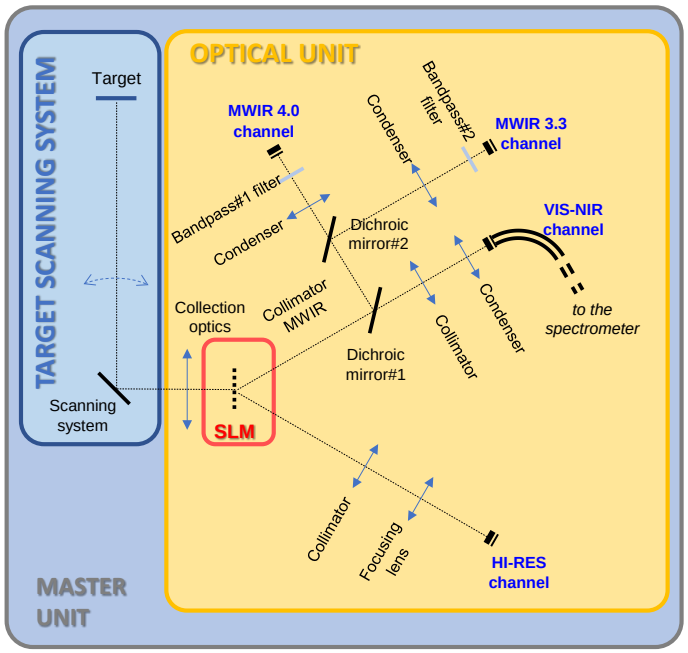

Figure 2. General layout of the SURPRISE demonstrator with detail of its optical section.

The scene is scanned along two axes by means of a suitable scanning system. The fore-optics provides the image of the observed portion (target) of the scene on the image plane field stop at which the SLM is placed. For the sake of clarity, here the SLM is represented as it is working in transmission mode. The image captured in the instrument's Instantaneous Field Of View (IFOV) corresponds to a 'macropixel' on the SLM. Spectral splitting is applied after the SLM-based coding stage by means of dichroic mirrors and is followed by the spatial integration stage implemented by the condensers. The signal is further spectrally filtered (or dispersed by the spectrometer for the VIS-NIR channels) and finally acquired in the spectral bands of interest by suitable detectors. Specifically, the SURPRISE demonstrator has two channels in the MWIR and ten channels in the VIS-NIR spectral range. The demonstrator is completed with an additional block constituted by a high-resolution panchromatic camera that is used for alignment and validation purposes.

In the SURPRISE demonstrator, the fore-optics provides the image of the observed portion (target) of the scene on the image plane field stop at which the SLM is placed. The image of the target on the SLM corresponds to a 128x128-micromirror area (macropixel). Depending on the Super-Resolution (SR) factor applied, these 128x128 micromirrors can be grouped (binned) from 4x4 (so that one micropixel is made of 4 x 4 micromirrors and this corresponds to the maximum SR, equal to 32 x 32) up to 32 x 32 (so that one micropixel is made of 32 x 32 micromirrors and this corresponds to the minimum SR, equal to 4 x 4).

On the whole, the SURPRISE demonstrator - which is currently under assembly at CNR-IFAC lab – will achieve at least a 4-fold super-resolution factor. Based on the results of the preliminary tests of image reconstruction of simulated datasets, we expect to achieve Compression Ratio of 50%. In the next months, native encryption will be studied and information extraction - directly from the acquired random projections - will be also explored, with the aim of enabling on-board data processing capabilities.

4. CONCLUSIONS

CS paradigm paves the way to the design of novel instrumental concepts that rely on SLM technology to implement super-resolved compressive instrument for EO applications. Here we presented the working principle and the overall architecture of a super-resolved CS demonstrator under development at CNR-IFAC labs in the frame of the EU-funded SURPRISE project. The demonstrator features a compressive architecture to implement a super-resolved instrument with ten channels in the VIS-NIR and two channels in the MIR. Besides the feature of merging the acquisition and compression phases of the image into a single step, it allows to reach a super-resolution factor of at least 4x4 in the images reconstructed at the end of process. Impact on EO applications is expected not only in terms of native compression, on-board processing and encryption capabilities, but also in terms of increased GSD with respect to that one provided natively by the number of the detector's pixels as in traditional instruments.

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