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SURPRISE laboratory demonstrator: outcomes of the laboratory test campaign

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ABSTRACT

A laboratory demonstrator of a super-resolved, Compressive-Sensing (CS)-based instrument was designed, assembled and tested in the framework of the H2020 SURPRISE project (SUper-Resolved comPRessive InStrument in the visible and medium infrared for Earth observation applications). The instrument is a multispectral imager working in the VIS-NIR and the MIR spectral ranges for Earth Observation (EO) applications. The imager relies on the concept of the single pixel camera: the target image is acquired by using a sequence of coded measurements implemented by means of a Digital Mirror Device (DMD) and a single-pixel detector. The image is reconstructed at the same spatial sampling of the coding mask thanks to the use of the CS paradigm that optimizes the reconstruction using only a limited number of measurements. The demonstrator foresees the use of a scanning system to perform the acquisition of the entire scene. It acquires a multispectral image with ten spectral channels in the VIS-NIR and two channels in the MIR. The super-resolution factor can be adjusted from 4 x 4 to 32 x 32. The DMD used in the demonstrator was a DLP®7000, manufactured by Texas Instruments Inc. and reworked in order to replace the glass window to gain transparency in the MIR bands. The target image reconstruction is obtained by using *ad-hoc* CS reconstruction algorithms. The results obtained using the SURPRISE demonstrator showed good potential for novel EO instruments with enhanced capabilities in terms of target spatial sampling and native compression.

Keywords: Compressive sensing, Super resolution, DMD, multispectral imager, medium infrared, Earth Observation

1. INTRODUCTION

The use of Earth Observation (EO) data is becoming increasingly important for monitoring the status of our planet. Presently, however, there are still several limitations in the use of EO data, mainly due to limited revisit time and spatial resolution. This is particularly true for payloads working in the infrared spectral range and placed on geostationary platforms where the scarce spatial resolution (order of kilometers) is balanced by an almost continuous revisit time (tens of minutes). A frequent revisit time is desirable for monitoring the risk associated to events such as fires or eruptions, but at the same time a good spatial resolution is also needed for an accurate evaluation of the risk and its evolution.

In the framework of EU-funded H2020 SURPRISE project – acronym of "SUper-Resolved comPRessive InStrument in the visible and medium infrared for Earth observation applications" - the potential use of the Compressive Sensing (CS) paradigm for the development of a CS-based payload working in the in the visible (VIS) - Near Infrared (NIR) and in the Medium InfraRed (MIR) spectral ranges from geostationary platform was investigated. In particular, the project aimed to

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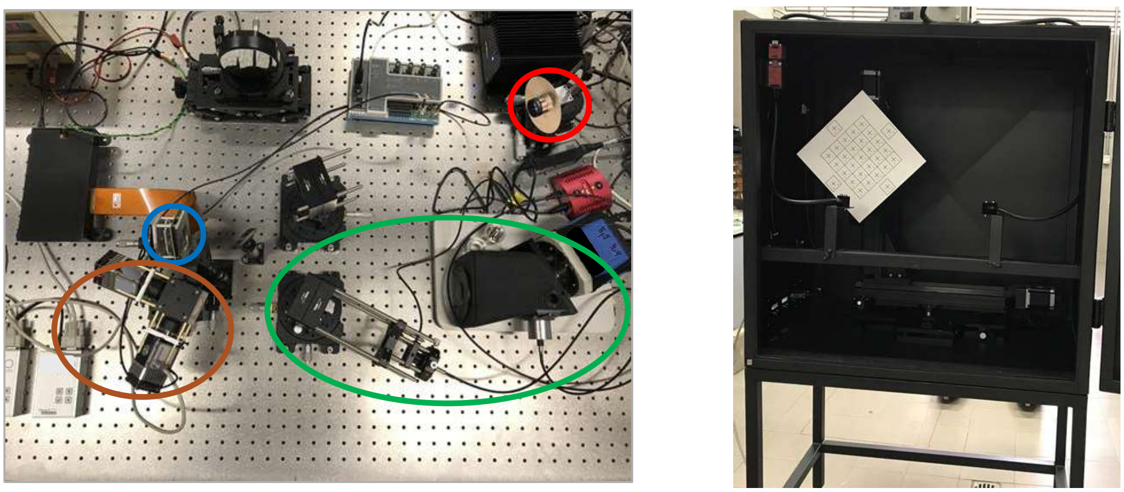
the design, construction and test of a laboratory demonstrator with enhanced performance in terms of spatial sampling, onboard processing and encryption capabilities.
In this paper, results of the laboratory measurements verifying the performance of the multispectral imager in terms of achieved spatial super resolution and image quality at different Compression Ratio (CR) are presented. The results obtained using the SURPRISE demonstrator showed good potential for novel EO instruments with enhanced capabilities in terms of target spatial sampling and native compression.

2. SURPRISE DEMONSTRATOR

The laboratory demonstrator uses a commercial Digital Micromirror Device (DMD) as the core element to implement a CS architecture [1, 2]. The demonstrator is a multispectral imager with ten spectral bands in the VIS-NIR and two spectral bands in the MIR. The imager implements a single pixel camera architecture [3] in which the target image is acquired by using a Digital Mirror Device (DMD) to obtain a sequence of coded measurements and a single-element detector. A contiguous ensemble of DMD micromirrors defines a "macropixel" on the DMD, each macropixel matching one element of the detector. In this way each macropixel is made up of NxN micropixels. The image is reconstructed at the same spatial sampling of the coding mask, but by means of the acquisition of a lower number of samples with respect to a traditional system thanks to the use of the CS paradigm that optimizes the reconstruction by using only a limited number of measurements. Since the SURPRISE instrument is conceived to operate in whiskbroom mode, the demonstrator foresees the use of a scanning system for performing the acquisition of the entire scene. The super-resolution factor, i.e. the ratio between the number of pixels of the reconstructed image and the number of pixels of the detector, can be adjusted from 4 x 4 to 32 x 32.

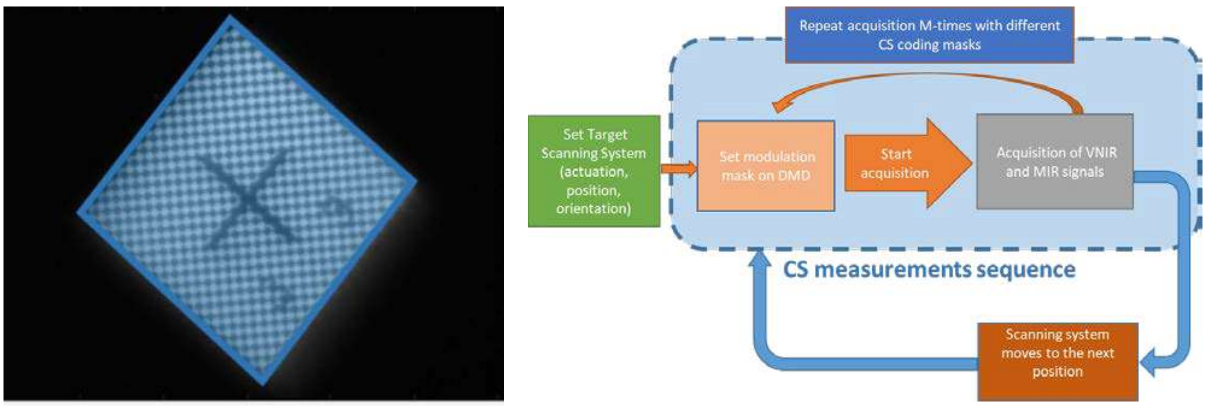


(a) (b)

Figure 1. (a) SURPRISE demonstrator mounted on the optical bench: down-left MIR arm (inside the brown ellipse), down-right VIS-NIR arm (inside the green ellipse), center-left DMD (inside the blue circle) , top-left primary mirror of Newtonian telescope, top-right high resolution camera (inside the red circle). (b) SURPRISE Target Scanning System with the alignment target mounted inside.

The instrument fore-optics is a custom Newtonian telescope that focuses the observed image on the DMD. The DMD-coded image is spectrally split through two arms by using a system of dichroic mirrors: the first arm is equipped with a spectrometer in the VIS-NIR wavelength range, the other is equipped with a further dichroic mirror for spectrally split the infrared radiation and fed the latter in two MIR single-pixel detectors. In this way, the simultaneous acquisition of the observed target both in the VIS-NIR and in the MIR bands can be achieved. The demonstrator foresees also the use of a high-resolution camera for optical alignment and system setting. The core part of the demonstrator is a commercial DMD produced by Texas Instrument Inc. In particular, the selected DMD is the DLP®7000 reworked in order to replace the original glass window, transparent only in the VIS-NIR range, with a sapphire window, that has a broader transparency and permits to acquire images in both VIS-NIR and MIR bands [4]. In Figure 1a, the laboratory set-up of the demonstrator

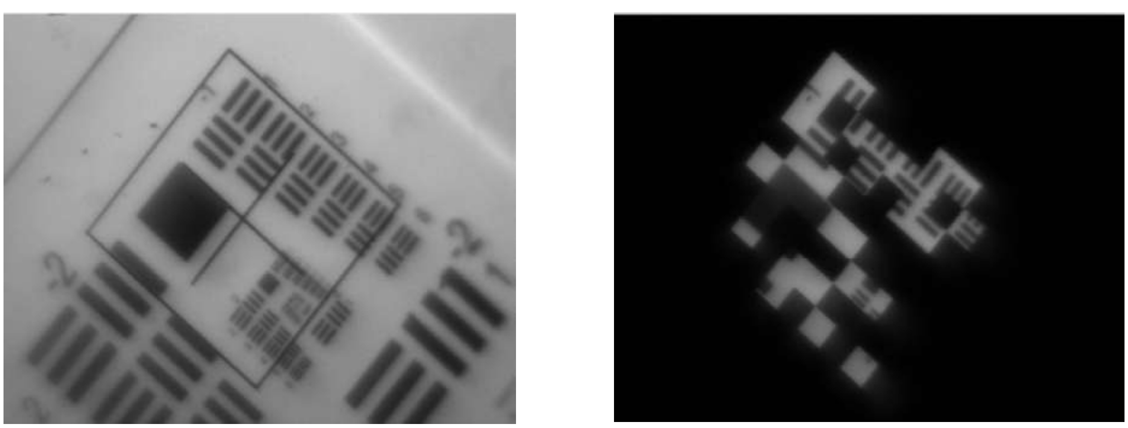
is reported. The target image reconstruction is obtained by using *ad-hoc* CS reconstruction algorithms. In Figure 1a, the laboratory set-up of the demonstrator is reported. Figure 1 shows also the high-resolution camera used for optical alignement.
Since the demonstrator acts as a whiskbroom multispectral imager, the entire scene is observed one “macropixel” at a time, thanks to the use of a target scanning system (shown in Figure 1b). The micrometric movements of the target are obtained by means of linear motion stages, controlled by the central unit, that guarantees also the synchronization between target movement and data acquisition. Figure 2a shows how the “macropixel” of the target as it is seen by the high resolution camera when the DMD is set to obtain a 32x32 checkerboard. The sequence of operations needed to complete the acquisition of a “macropixel” of the target image is schematically represented in Figure 2b.



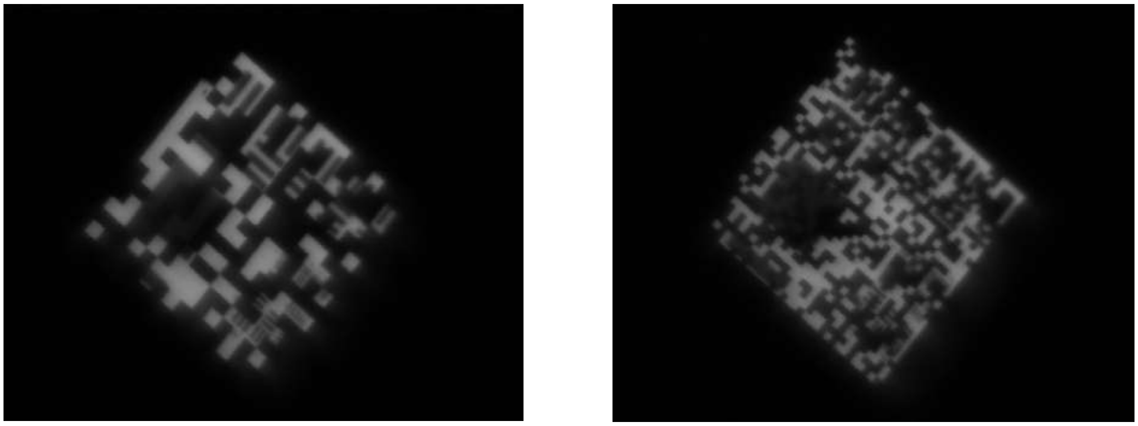
(a) (b)

Figure 2. (a) Central “macropixel” of the alignment target with superimposed a 32x32 checkerboard, as it is seen by the high resolution camera. (b) Block diagram of the acquisition procedure implemented with the SURPRISE demonstrator.

The sequence of operations starts with verifying the alignment of the target scanning system with the optical system. Then the target is positioned to acquire the first “macropixel” (Figure 3a); subsequently a modulation mask is set on the DMD and the acquisition starts: each measurement is acquired by using a different mask. Modulation masks are random binary masks, depending on the chosen SR factor; modulation masks are made of a different number of pixels. In Figure 3b, 3c and 3d, modulation masks for different SR are shown.



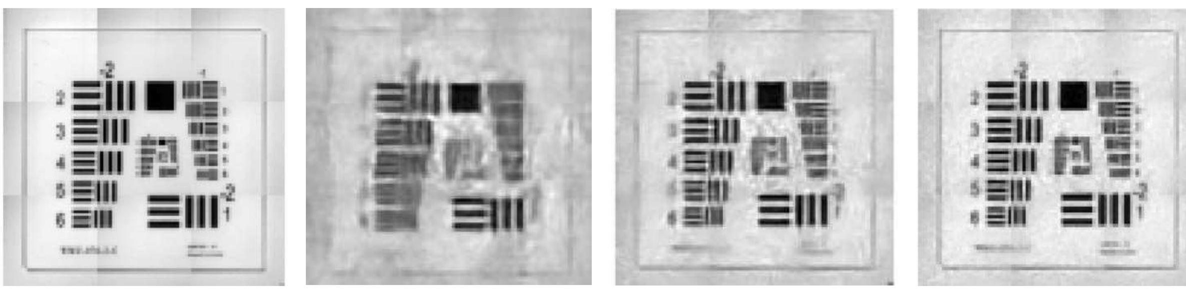
(a) (b)



(c) (d)

Figure 3. (a) Alignment of the target with the acquisition system by means of the target scanning system, as it is seen by the high resolution camera. (b) SR factor 8x8 modulation pattern on a “macropixel” of the target, (c) SR factor of 16x16, (d) SR factor of 32x32.

After the CS acquisition, the target image is obtained from the measurements by using an *ad-hoc* reconstruction algorithm. For the SURPRISE project, the reconstruction algorithm was developed with deep-learning techniques based on ISTAnet [5]. Examples of the results of the reconstruction procedure are reported in Figure 4, for the target image USAF-1951 resolution chart, for different CR values.



(a) (b) (c) (d)

Figure 4. (a) Reference image with 32x32 SR. (b) Reconstructed image with CR of 25%, (c) Reconstructed image with CR of 50%, (d) Reconstructed image with CR of 75%.

3. CONCLUSIONS

The SURPRISE laboratory demonstrator successfully showed the potential of Compressive Sensing (CS) technology for EO. By implementing a multispectral imager based on the single-pixel camera concept, we have demonstrated several key advancements in:

- Super-resolution capabilities: the demonstrator achieved adjustable super-resolution factors ranging from 4x4 to 32x32.
- Multispectral imaging: the instrument successfully acquired images in ten VIS-NIR spectral bands and two MIR bands, providing rich spectral information.
- CS-based reconstruction: using ad-hoc CS reconstruction algorithms, including deep learning techniques based on ISTAnet, we were able to reconstruct high-quality images, even from a limited number of measurements.
- Flexible compression ratios: the system demonstrated effective image reconstruction at various compression ratios, showcasing its adaptability to different data transmission constraints.

- DMD-based architecture: the use of a modified DLP®7000 DMD enabled simultaneous imaging in both VIS-NIR and MIR spectral ranges, expanding the instrument's versatility.

These results indicate that CS-based instruments like the SURPRISE demonstrator have significant potential for future EO missions, particularly from geostationary platforms. The ability to achieve high spatial resolution while maintaining frequent revisit times could greatly enhance monitoring capabilities for dynamic phenomena such as fires or volcanic eruptions.

Future work should focus on further optimizing the reconstruction algorithms, exploring additional spectral bands, and addressing challenges related to scaling the technology for space instrumentation. The native compression capabilities of the CS approach also warrant further investigation for reducing downlink data volumes in future missions.

In conclusion, the SURPRISE demonstrator has successfully validated the concept of a super-resolved, CS-based multispectral imager, paving the way to a new generation of EO instruments with enhanced spatial resolution, spectral capabilities, and onboard processing efficiency.

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