Single Pixel SWIR Imaging using Compressed Sensing

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***Abstract*—Conventional infrared camera systems capture the scene by measuring the radiation incident at each of the thousands of pixels in a focal plane array. In compressed sensing a relatively small number of measurements from the scene is combined with an sparse construction procedure to recover a full resolution image. Using compressive sensing an image can be acquired with content of a high resolution image captured with high resolution focal plane array while using smaller, cheaper and lower bandwidth components. A single pixel camera in SWIR, which combine a digital micromirror device (DMD), an InGaAs photodiode and a compressive sensing reconstruction procedure is presented. In many applications the SWIR spectrum provides significant benefits over the visual spectrum. For example SWIR enables separation between camouflage and vegetation and penetrate to some extension fog and smoke which enable imaging through scattering media. Furthermore, SWIR sensors can be used for passive imaging in the dark due the night-glow of the sky that provides SWIR illumination.**

I. Introduction

In compressed sensing a high resolution image is constructed from a large number of measurements from a single-pixel, or few-pixel, sensor. Even if the number of measurements is large it is much smaller than the resolution of the constructed high resolution image. In this paper we present a single-pixel camera system that combines a single-pixel detector in the SWIR spectrum with a digital micromirror device (DMD). Image reconstruction methods is then used to construct a high resolution image from a set of measurements from the single-pixel sensor. The acquired high resolution image reconstructed from the set of single-pixel measurements contains the equivalent

The motivation of building a compressive sensing single-pixel camera system in the short-wave infrared (SWIR) spectrum is motivated by the relatively low cost of the detector and the fact that in some applications the SWIR spectrum provides significant benefits over ordinary visual spectrum or the near-infrared (NIR) spectrum [1]. SWIR enables separation between camouflage and vegetation and penetrates, to some extension, fog and smog which enables imaging through certain media (see figure 1). The illumination from the night-glow of the sky makes SWIR usable as a passive image sensor even in the dark.

II. Background

Compressed sensing and reconstruction of high resolution images from ensemble of single pixel cameras or low resolution cameras has been extensively studied mainly in the visual spectrum. In 2006 [2] Rice University presented a single-pixel camera combined with compressed sensing high resolution image reconstruction method. They outlined the principle architecture of a single-pixel camera using DMD.

Petrovici et al [3] are analysing the influence of the random distribution of on/pixels in the scene. The propose and evaluate a Non-Uniform samplig strategy which seems to give a more accurate reconstruction with fewer samples at least if scene contains a large amount strong edges.

Compressed sensing and reconstruction on high resolution images from ensemble of single pixel cameras in the short wave infrared (SWIR) spectrum has not been extensively studied.

McMackin et al [4] presents a singel-pixel system in the SWIR spectrum called InView that utilize compressed sensing to construct a high resolution image from an set of measurement. They use a high resolution DMD to modulate the light that enter the sensor. The single-pixel camera combined with the DMD and compressed sensing reconstruction algorithm makes it possible to create images with the resolution of the DMD. They also implement a adaptive compressed sensing strategy that detect bright regions, caused by for example sun light, that normally would decrease the dynamic range of the camera. The adaptive compressed sensing method automatically detect and remove such regions/pixels. Använder Inte EPK

Chen et al [5] present a low resolution (64×64 pixels) camera system in the SWIR spectrum that utilize compressed sensing to construct high resolution images (4096×4096 pixels). The spatial resolution of single-pixel cameras combined with compressed sensing to construct images is high (and mainly depends on the resolution of the DMD) while the temporal resolution is low. By increasing the number of pixels in the sensor the temporal resolution is increased.

du Bosq et al [6] evaluate a single-pixel SWIR camera combined with compressed sensing high resolution image construction methods. They show that sufficient high resolution images can be constructed from a set of single-pixel measurement using compressed sensing construction methods. Classification of images containing different types of weapons are used to evaluate the single-pixel camera system. Few details about the system is presented in the paper, instead the focus is on the evaluation of the system.

Edgar et al [7] present a single-pixel system composed

Fig. 1. Images of a volcano scene containing smoke captured using a visual and SWIR camera. SWIR penetrates fog and smog which enables imaging through certain media (source https://www.digitalglobe.com/).

of a SWIR and visual sensor that simultaneously reconstructs SWIR and visual images of resolution 32×32 pixel in realtime ($10Hz$).

Radwell et al [8] present a single-pixel microscope system which combine a SWIR and a visual camera to reconstruct high resolution images (64×64 pixels) in near realtime.

Nayar et al [9] introduce the DMD as a generic programmable camera model with virtual per-pixel exposure time control.

III. Compressed sensing - Image Reconstruction

The following section contains a short presentation of compressed sensing and a high resolution image can be reconstructed from an ensemble of single pixel images. General good introduction to sparse representation and compressed sensing can be found in [10], [11], [12]. In compressed sensing sampling and compression is combined in a joint measurement process. Instead of measuring incoming light from specific locations in the scene at hand, inner products between the scene and an set of random test functions are measured. Each measurement can be considered as a random sum of pixel values randomly distributed in the scene.

Let x be an vectorized image with elements $x[n]$ where $n = 1, \cdots, N$ where N is the number of elements in the image.

The first step in compressed sensing involves finding a sparse representation of a vectorized image x in a suitable orthonormal basis. The image can be written as

$$x = \sum_{i=1}^{N} \alpha_i \psi_i \quad (1)$$

where $\{\psi_i\}_i^N$ are the basis vectors and $\alpha = (\alpha_1, \cdots, \alpha_N)$ are coefficients for image x in the base. This can concisely be written $x = \psi\alpha$. The goal is to find a basis ψ where the coefficients α is sparse (i.e. most of the elements in α is 0).

Let $\{\phi_m\}m = 1^M$ be a set of test function and let $y[m] = \langle x, \phi_m \rangle$ i.e. the inner-product between the test function ϕ_m and the image m. Stacking the measurements $y[m]$ into a $M \times 1$ vector and the test-functions ϕ_m^T into a matrix ϕ where each row is a test-function in the $M \times N$ matrix ϕ. Then measurements can be written as

$$y = \phi x = \phi\psi\alpha \quad (2)$$

In this formulation the test-functions are random pattern of DMD (random on/off states), y is the measurement of the single-pixel SWIR sensor and x is the high resolution image one wants to reconstruct.

The solution - a high resolution image from a set of measurement and test-functions - can be found by solving the optimization problem

$$\hat{\alpha} = argmin_{\alpha}\{||\alpha||_1\} \text{ subject to } ||y - \phi\psi\alpha||_2 < \epsilon \quad (3)$$

Needel and Ward [13] presented a image reconstruction algorithm using total variation minimization.

For more information on this algorithm the reader can visit the webpages $http : //dsp.rice.edu/cscamera$ (Rice Single-Pixel Camera Project), $www - stat.stanford.edu/candes/l1magic$ and $sparselab.stanford.edu$ for available implementation.

IV. System Architecture

In our work, we have designed a short wave Infrared (SWIR) single pixel camera by using a Digital Micro Mirror Device (DMD) operating as a Spatial Light Modulator (SLM). This type of system can, by Compressive Sensing (CS) capture an image of a scene even if only one (1) detector pixel is used. A DMD placed in the image plane operates as a digitally controlled pixelated binary component by reflecting light from the scene in one or the other of two stable directions. A CS-image of the scene can be created by measuring the optical signal/levels from a large number of different pseudo random binary patterns on the DMD, the more patterns, the higher image quality can be achieved at the expense of frame rate. An image with the same resolution as the DMD can be achieved, but by lowering the resolution and/or Field Of View (FOV) the number of patterns it takes to build up an image can be reduced significantly.

A visual/NIR camera (detector matrix) is also included in the system and placed in one of the "arms" so real time images of the DMD and scene can be captured.

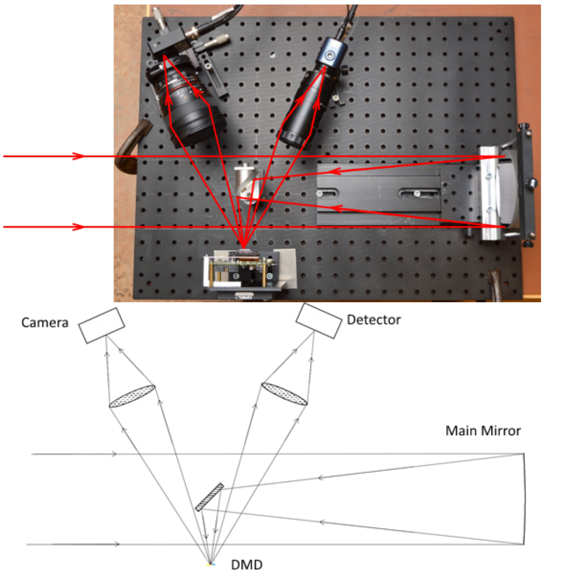

Fig. 2. A simplified sketch and a photograph of the CS-camera. The main optics is reflective and based on a Newtonian telescope design. The system is focused by moving the main mirror along a rail.

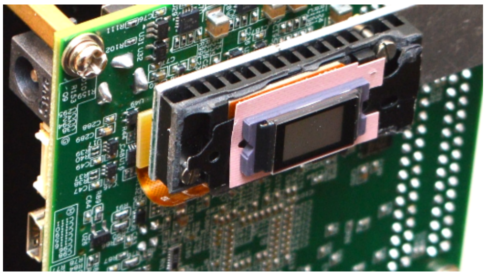

Fig. 3. A photograph of the DMD (Texas Instruments DLP4500NIR) mounted on the Texas Instruments DLP LightCrafter 4500 Evaluation Module. The lightsource is removed to expose the DMD.

Selected pixels depending of the mirror settings of the DMD can thus be reflected to the either the single pixel SWIR-detector or the visual/NIR camera. An advantage of including a camera is to simplify setup, alignment and focusing of the system (by moving the main concave mirror on a rail) because a visual/NIR image is available directly. A disadvantage of this camera (instead of e.g. an optical beam dump) is that reflections back to the DMD can occur thus reducing the performance of the single pixel camera to some degree.

The optical system is based on a Newtonian telescope design with "off-the-shelf" components and is mounted on an optical breadboard as can be seen in the figure 2. Advantages of using reflective optics instead of refractive is that chromatic aberration is eliminated and that the optical system works over a very wide range of wavelengths limited by the glass optics in front of the SWIR-detector and protecting glass on the DMD (700-2500 nm). The aluminium main concave mirror (Edmund Optics, 32-065-522, FL=445,5 mm, D=108 mm F#=4.1) focuses the image via a 45° tilted secondary mirror (Edmund Optics, 30-837) on the DMD (Texas Instruments DLP4500NIR) where the individual mirrors on the DMD can be tilted

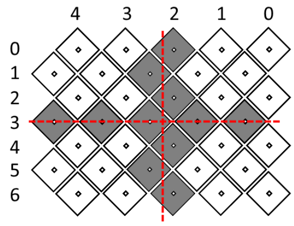

Fig. 4. The micromirrors on the DLP4500NIR are oriented in a diamond formation as can be seen in this illustrating sketch. The adressing of Row 3 and Collumn 2 are shadowed and marked by red lines. As can be seen a single collumn is thicker than a row which means that a square input image to this DMD results in a rectangular output.

independently between two stable states (12° or $+12^\circ$) which gives reflection directions of 24° or $+24^\circ$. The DMD, seen in figure 3, is mounted on a projector (Texas Instruments DLP LightCrafter 4500 Evaluation Module) which has had its light source removed. The visual camera (Edmund Optics EO-0413M with the objective Computar MLH-10X) is focused on the DMD to capture images of the scene and DMD. The FOV of the system is 1.27° x 0.79° and is limited by the size of the DMD ($9.9 \times 6.2mm$). To collect the light to the SWIR-detector an off-the-shelf camera objective designed for visual spectrum is used (SAMYANG F#1.4/50mm), the transmission of this objective is unknown and thus some loss of the transmitted light can be expected especially at longer wavelengths. The InGaAs single pixel detector used is sensitive between 800-1700 nm and has a diameter of 2 mm and detector area of 3.14 mm^2 (Thorlabs PDA20C/M).

V. Measurement and Image Extraction

To create an image of the scene multiple binary pseudorandom patterns of a resolution of 64×64 (50/50 bright/dark pixels) is sent in sequence to the DMD via a HDMI-port using a standard Windows laptop. The binary patterns are saved as a video file (filetype avi) and to increase the FOV rescaled by a factor of 4 giving the binary pattern a total resolution of 256×256, thus a single pixel is built up by multiple micromirrors as is illustrated in figure 4. Because the total resolution of the DMD is 912×1240, the pattern is covering a small part centered on the DMD surrounded by a dark frame in the view of the single pixel detector (bright in the view of the visual camera). An image of a single binary pattern can be seen in the figure 5.

A standard laptop with Windows 7 and a video player (VideoLan VLC) is used to send the patterns to the DMD at a low video frequency (30 Hz), to assure that no video artefacts such as lost frames or frame tearing occurs. A much higher video frequency is possible if the images/binary patterns are stored on the internal memory of the DLP LightCrafter 4500. Each binary pattern are separated by black frames so signal analysis is made simpler. The DLP4500 evaluation module is operated in Pattern Sequence Video Mode which applies no image processing.

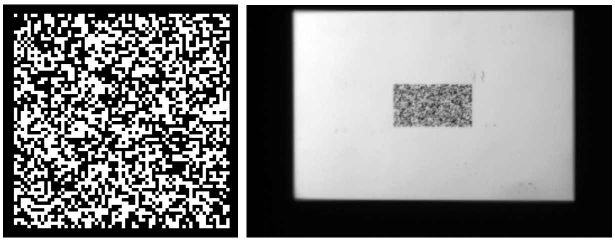

Fig. 5. Left: An example of a 64 × 64 binary pseudo random pattern. Right: An image from the VIS/NIR camera when the system is directed at a white board. The FOV of the VIS/NIR camera is a little larger than the DMD. In this example the binary pattern is scaled by a factor of 4 resulting in a total pattern resolution of 256 × 256 covering a small part of the 912 × 1240 resolution DMD. Bright pixels in the VIS/NIR camera turns up dark in the SWIR single pixel detector and vice versa.

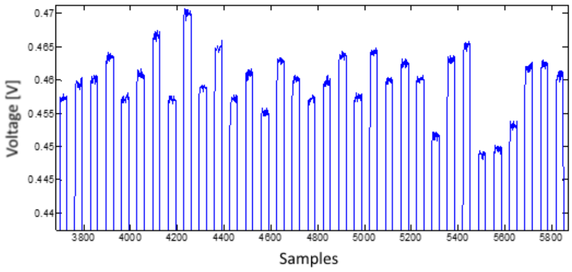

Fig. 6. An example of a received signal measured from the SWIR detector (5 kS/s, 30 samples per DMD-pattern/frame). Half of the frames on the DMD is completely dark to simplify separation between each pseudo random binary pattern. The SWIR-detector is set to maximum amplification (70dB).

The signal from the detector is captured by a Data Acquisitioner (DAQ, National Instruments NI USB-6211) and saved on a computer. An example of a received signal can be seen in figure 6. The image is reconstructed using a standard algorithm tvqc-logbarrier (i.e. solving the minimization problem described in section III).

VI. Results - Image Reconstructions

Signals and extracted images presented in this section are from an indoor measurement at a distance of 50 meters. A visual photograph of the scene can be seen in figure 7. A 150 Watt Halogen spotlight is illuminating the scene from about 1 meter.

Image reconstruction of the scene with increasing number of samples are shown in figure 8. Reconstruction with few samples gives an cartoonish impression of the constructed image. The constructed images seems to be composed of homogeneous region with constant intensity (i.e. piecewise constant reconstruction). Reconstruction using Total Variation as a regularization term gives a piecewise solution with a cartoonish impression [14]. As the number of sample increase fine scale details are added to the reconstruction.

VII. Conclusion

Initial results show that it is possible with the SWIR optical system and compressed sensing to reconstructed images of a scene up to at least 50 meters away, which was the longest range tested. Using a standard method (tvqc-logbarrier in l1 magic) to reconstruct the measured signal we can see that the image quality as expected is increased the more pseudo random binary patterns used. A better image quality could probably be obtained by optimizing the reconstruction method and a higher light throughput could be obtained by choosing optics in front of the detector designed for SWIR. We have also proven that it is possible with the same system to capture an image in real time using a standard visual/NIR camera.

Fig. 7. Photograph of the scene used in the experiment at 50 meters. The FOV of the CS-camera is marked by the red box. To the left is a black painted plate and to the right is logo on a printed paper.

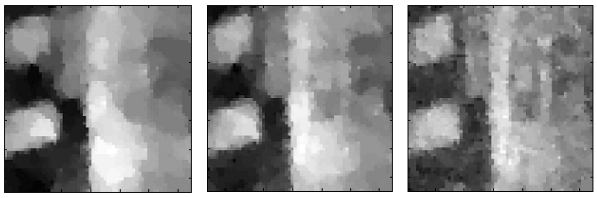

Fig. 8. Image reconstruction of the scene at 50 meters using 500, 750 respective 1250 samples. The pseudo random binary pattern has a resolution of 64 × 64. Reconstruction using few samples gives an cartoonish impression, more details are added as the number of samples in the reconstruction increases. The large scale geometric structure can be reconstructed with few sample, while fine scale texture require more samples.

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