Detection and Localization of Light Flashes Using a Single Pixel Camera in SWIR

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ABSTRACT

A high-resolution single pixel camera for long range imaging in the short-wave infrared (SWIR) has been evaluated for the detection and localization of transient light flashes. The single pixel camera is based on an InGaAs photodiode and a Newtonian telescope, with a digital micromirror device (DMD) operating as a coded aperture. Images are reconstructed using compressed sensing theory, with Walsh-Hadamard pseudo-random measurement matrices and a total variation based regularization method (TVAL3). Results from experiments with light flashes are presented and the potential use of the camera for muzzle flash detection and localization is discussed.

1.0 INTRODUCTION

The primary signatures to detect snipers are acoustic signal, optical signal from the muzzle flash (visual and IR) and pre-shot laser retro-reflection from the optical sight. In the visual spectrum, the muzzle flash can be extremely weak and hard to detect, especially in daylight and in particular with signature suppressors mounted. Based on temperature and heat signatures alone, the optimal spectral ranges to optically detect sniper fire, mortar fire or rocket propelled grenades (RPGs) would be around 2.8 µm and 4.5 µm (see example from a sniper gun shot in Figure 1). The MWIR range (3–5 µm) would therefore be seen as the best choice for a hostile fire indication (HFI) system [1, 2]. The MWIR range is however associated with larger size, weight and power requirements and cost (e.g. higher SWaP-C). Systems operating in the SWIR bands 0.8–1.7 µm and 1.1–2.5 µm have advantages of potentially lower SWaP-C, while also being subjected to strong EO signatures from the flash. The former SWIR band is usually preferred due to the availability of uncooled InGaAs FPAs in this spectral range. As the distance increases, the radiances in the bands 1.7–2.0 µm, 2.4–3.4 µm and 4.0–4.5 µm decrease rapidly because of the atmospheric transmission [1]. An example of the spectral distribution of a 50 caliber gun and images of a sniper rifle at 1000 meters in SWIR and MWIR can be seen in Figure 1. Discrimination from false alarms may be done on the basis of intensity, spectral content and temporal profile [4].

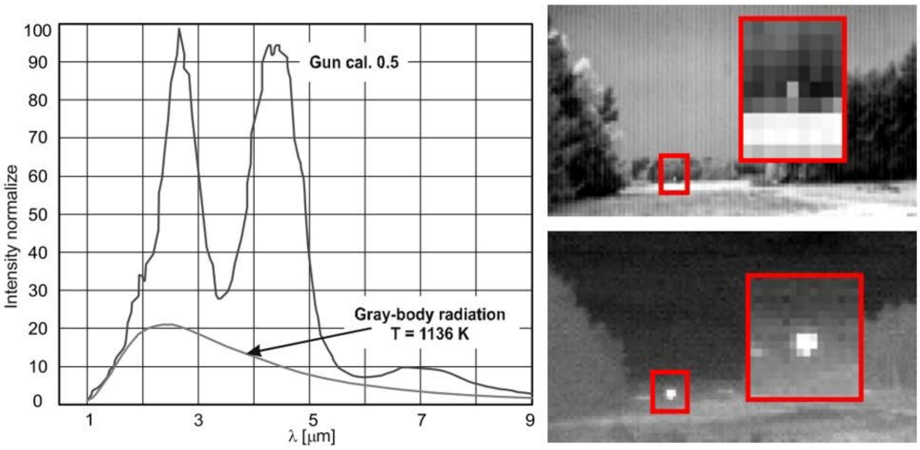

Figure 1: Left: The spectral distribution from a secondary flash. The weapon has a caliber of 0.5 (barrel length 36 in). [1] Top right: Muzzle flash from a sniper rifle at 1000 meters recorded in SWIR (0.8–1.7 μm). Bottom right: Same flash in MWIR (3–5 μm). The red rectangles show enlargements at the rifle position. [3]

Munitions flashes, such as gunshots, explosions, missile launches and kinetic ammunition are high-speed phenomena with time durations from sub-milliseconds to a fraction of a second. The temporal signature of a muzzle flash in various spectral bands can be seen in Figure 2. As can be seen, the flashes in SWIR are typically less than 1 ms long. [5]

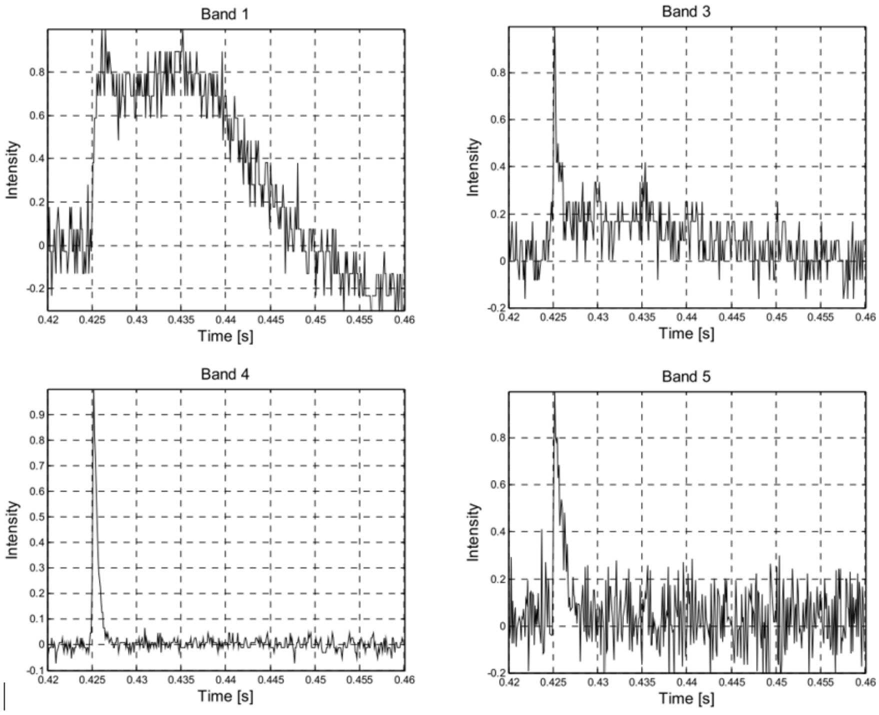

Figure 2: The intensity recorded for a 7.62 cal gun for multiple spectral bands, shown during a 40 ms duration and normalized to the peak value. Band 1 is 0.35 - 0.65 μm, band 3 is 1.46 - 1.79 μm, band 4 is 2.13 - 2.57 μm and band 5 is 3.0 - 4.80 μm. In the 0.35 - 0.65 μm band, only scattered light from the sun and the flash itself was observed. [5]

In Brannlund's work from 2013 [6], a combined hostile fire and optics detection system was tested, using a laser illuminator and a high speed FPA camera in SWIR. Krieg et al [3] demonstrated a system in 2016, using 19 single element detectors to detect muzzle flashes. Additionally, two acoustic sensors were integrated to reduce false alarms rate, based on results from the EDA SNIPER project [7]. Gil Tidhar proposes a hostile fire indication (HFI) system with two FPA sensors, the first operating in SWIR and the other one in the visible band. With this solution sun-glints and other light sources such as car headlamps can be cancelled out, as the spectra of such sources is typically different to that of a muzzle flash. [8] Trzaskawka et al presents an initial concept of a cooled electro-optical sensor unit in MWIR for sniper detection purposes and discuss the characteristics of muzzle flashes [1].

Standard cameras with typical frame rates of 30 or 60 Hz are not fast enough for detection of snipers and the problem therefore requires non-standard high-speed imaging solutions. But even if the frame rate is high, it still needs to be significantly higher than 1 kHz to resolve the temporal signature, which is normally beyond the capability of most sensors [5]. The flash can be detected with such a device, but it may only be resolved in a single frame thus making it susceptible to false alarms. The high data rate of a FPA is also a problem, because the algorithm needs to analyse all the pixels in each frame and compare it to the previous one to detect the fast rise in pixel value.

Conventional cameras capture the scene by measuring the light at each of the thousands or millions of pixels. In Compressed Sensing (CS), a relatively small number of measurements from the scene is combined with sparse reconstruction procedures to recover an image using only a single or a reduced number of pixel detectors. CS exploits the fact that natural images are compressible or sparse in some basis and therefore only a few measurements relative to the image resolution are needed (sub-Nyquist) to reconstruct the image. Two constraints must be fulfilled in order to utilize CS sampling: the image information needs to be compressible and the measurement matrix need to be incoherent with the sparse transform. The first constraint is fulfilled because it is known that natural images are compressible, using for example JPEG or JPEG2000 compression algorithms. The second constraint is fulfilled using a measurement matrix with a random characteristic. In CS, a high resolution image can be acquired at sub-Nyquist sampling rates while using smaller, cheaper and lower bandwidth components but with the expense of a longer acquisition time compared to standard cameras. [9, 10, 11]

Chen, J et al. [12] have described a method to detect light flashes in raw data using a CS-based single pixel camera (SPC) and a sliding window calculation process. They succeed in detecting 25 ms anomalies with an intensity 4% higher than the background. Cevher et al [13] have demonstrated a background subtraction method using an SPC to directly recover the foreground or sparse innovations of a scene. The object silhouettes are learnt directly without any extra image reconstruction.

This paper presents an initial concept of an HFI and sniper sight optics detection system, using CS and a low cost SPC with a background subtraction method implemented. Because a very fast photo diode collects the light in the SPC, the temporal resolution of the muzzle flash is not limited by the frame rate. SWIR images of a scene, including the sniper, can be generated while it simultaneously detects and localizes fast events such as the muzzle flashes. Also, the unique temporal signature of the flash can be measured directly in the detector signal, thus suppressing false alarms which is important for an operational system. Before the image is restored using CS methods, background reduction is performed directly on the raw data with data captured just before or after the fast event, making the data of the flash even sparser. Because the data of the flash is highly sparse, reconstruction of the image is possible using a single iteration in TVAL3 (Total Variation Augmented Lagrangian Alternating Direction Algorithm), reducing the computational time significantly. Restoration of the image to locate the flash is performed after it is detected and discriminated, thus minimizing the power usage. The system may also be used for optics (or cat's eye) detection if a laser is irradiating the scene, which means that a sniper may be detected and localized pre-shot. [1, 6] This functionality is to some degree demonstrated in the paper, when a small reflector is irradiated with a 1550 nm laser. It may also be possible to find the distance to the target by measuring the time-of-flight of the reflection, but this functionality is not demonstrated as the focus of this paper is on muzzle flash detection.

2.0 SINGLE PIXEL CAMERA (SPC) ARCHITECTURE

Our SPC platform consists of a low cost DMD (DLP4500NIR, 912x1140, 0.7-2.5 µm) and a large area detector InGaAs photodiode (Thorlabs PDA20C/M, 0.8-1.7 µm). The light from the "active" micromirrors is collected by a "light bucket" - the detector and a 50 mm fixed focal length lens (f/1.4, 0.8-2.0 µm). The SWIR photodiode is not chosen for best system performance but to keep the system at a low cost. To capture an image pseudo-random patterns are streamed at 1440 Hz to the control unit (DLP LightCrafter 4500). This speed is slow compared to other available DLP units (up to 32 kHz) and thus too slow to resolve a fast muzzle flash. To compensate for this in the measurements a "slow" 25 ms muzzle flash is simulated resulting in 36 patterns per muzzle flash.

The aluminium Newtonian telescope consists of a concave primary mirror (108 mm, F4.1), and a flat secondary mirror, focusing the scene onto the DMD, see Figure 3. The motivation to use a Newtonian telescope instead of a lens is partly that chromatic aberration is eliminated and partly that a reflective optical system works over a larger range of wavelengths. Good images can be captured at long range, but a drawback of the long focal length mirror design is that it has a narrow field of view (22x14 µrad). A visual spectrum reference camera is also mounted viewing the DMD to simplify focusing of the system. The SPC platform used in this paper is described in more detail in [14].

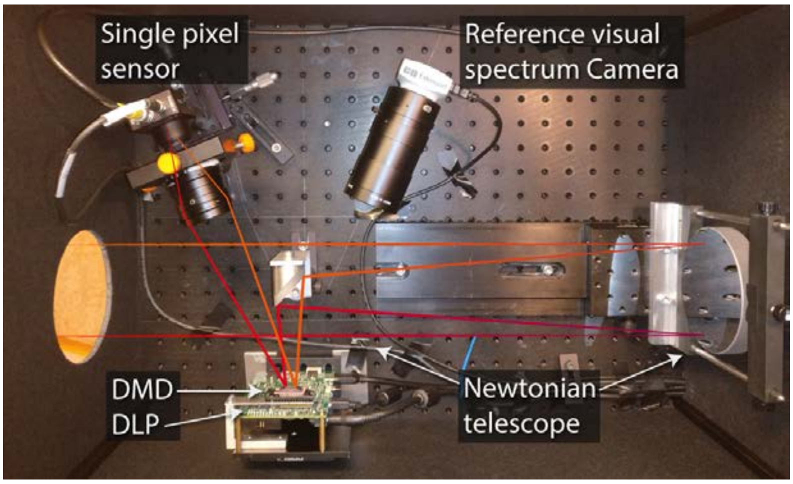

Figure 3: The single pixel camera architecture used in this work. The optics, DMD, reference camera and the single pixel sensor are shown including red lines showing the light path.

The single pixel sensor captures a scene by measuring the light intensity focused onto the detector reflected from the DMD (Digital Micromirror Device), or another SLM (Spatial Light Modulator). The DMD can quickly change patterns to obtain new measurements. M measurements are sampled to reconstruct an image with N pixels, where $M \ll N$. Each element in the measurement matrix is encoded as one or zero (turning the mirror onto or away from the sensor). The CS sampling model is defined as

$$y = \Phi x + \mathcal{E},$$

where x is the scene considered as an image rearranged as a one-dimensional array with N pixels, y is the sampled signal with M measurements, Φ is the measurement matrix and $\mathcal{E}$ is the noise. CS states that M can be relatively small compared to N, where the number of measurements needed to reconstruct an image depends on the sparsity of the image. Using an SPC where noise contaminates the signal and the scene may not be completely stationary, the number of measurements needed will increase in proportion to the noise and the change in the scene. Permutated Sequence Ordered Walsh-Hadamard matrix (PSOWHM) are used as measurement matrices, which can be generated and sent to the DMD, thus eliminating the need to store the measurement matrices in computer memory. PSOWHM has approximately the same characteristics and properties as an independent and identically distributed (i.i.d.) random matrix but generally needs a higher number of measurements for exact reconstruction of the image. Research has however shown that there is no significant loss in recovery of the image relative to the i.i.d. random measurement matrix [15]. The total variation (TV) based TVAL3 is used for image reconstruction. Natural images often contain sharp edges and piecewise smooth areas which the TV regularization algorithm is good at preserving. The main difference between TV and other reconstruction algorithms is that TV considers the gradient of signal to be sparse instead of the signal itself, thus finding the sparsest gradient. [16]

2.1 Muzzle flash detection and background subtraction

The system performance is increased by a method where the background signal, e.g. the raw signal of the scene collected just before or after the flash, is subtracted from the raw data of the muzzle flash event. In theory, the image information of the scene is removed and all that is left of the data is the small changes between the measurements and the muzzle flash, which is a very sparse signal. This method can be described as

$$y_{\text{reduced}} = y_{\text{pulse}} - y_{\text{background}},$$

where y_{pulse} is the signal with the light flash, $y_{\text{background}}$ the signal pre or post the muzzle flash with the same patterns as in y_{pulse} and y_{reduced} the background reduced signal. If nothing has changed between the two measurements the background reduced signal will only contain some noise. Using this method the number of DMD patterns needed to reconstruct an image of the flash can be reduced significantly. Detection of the muzzle flash event (or other light flashes), can be performed by thresholding the background-reduced signal, which can be done without reconstructing an image of the scene. The temporal signature of the fast event can also be compared with known signatures of muzzle flashes separating it from other natural events. The sparse background-reduced signal during the flash (acquired using only a few patterns) can be restored to an image using a single iteration in TVAL3. If the method is successful a dark image with some noise will be restored, where the brightest pixel is located at the position of the muzzle flash. Because a muzzle flash is a high-speed event, only a few patterns can be used to locate it – how many depends on flash length and DMD pattern rate so a high sampling rate is needed. Commercially, Texas Instruments DLP units are now available at sampling rates up to 32 kHz, which means that a 1 ms muzzle flash could be resolved by 32 patterns. This number of patterns is of course much fewer than needed to obtain a high quality image of the scene, but because of the very sparse nature of the muzzle flash (one or a few bright pixels) it is possible to reconstruct an image of such a spatially limited event.

2.2 Scene reconstruction

To obtain a high quality image of a natural scene, thousands of PSOWHM patterns are streamed to the DMD. The signal from the detector is greatly oversampled by a data acquisition device (PicoScope), such that multiple values for each measurement matrix (pattern) are obtained. Extraction of a single value for each pattern is performed by calculating the mean signal collected during a pattern shown, which creates the signal y[m] that can be processed by the reconstruction algorithm (TVAL3). In outdoor scenes, the intensity from the sun is however not constant. This will reduce the reconstruction performance, because the mean intensity of the measured signal is assumed to be stationary in CS. To compensate for the varying light conditions, a moving mean algorithm is applied to the measured signal. The number of neighbouring samples to calculate the mean value was set to 75, which corresponds to a window of 50 milliseconds. This method increases the image quality significantly for outdoor scenes, especially for high spatial resolutions that require longer exposure times.

3.0 EXPERIMENTS

A measurement of a bright sunlit outdoor scene (a March afternoon at 3 pm with mostly a clear sky) was performed to test the muzzle flash detection and localization functionality. To simulate the muzzle flash, a small reflector was mounted on a tree at a distance of 350 m and then irradiated by a pulsed laser placed next to the SPC. The laser parameters in the measurement was 7 W @ 1550 nm, 20 mrad divergence, 10 Hz pulse repetition frequency and a pulse length of 25 ms (a square wave with a duty cycle of 25%). The simulation of the muzzle flash is far from perfect. The size of the reflector (Ø7 cm) may be much smaller compared to a real muzzle flash and the temporal and spectral signatures will also differ to some extent.

Because the computer and hardware are limiting the pattern rate to only 1440 Hz, a 1 ms muzzle flash would only be resolved by 1.44 patterns, obviously not enough to locate it. Instead we simulated a 25 ms muzzle flash that at the current pattern rate is resolved by approximately 36 patterns. This would translate to a 1.125 ms long muzzle flash if a high speed DLP unit (with a 32 kHz sampling rate) would be used. In all the measurements (images), the FOVs are increased by binning the micromirrors, so the resolution of the patterns used was 512x1024.

4.0 RESULTS

The measurement when locating and detecting the muzzle flash were conducted in two steps; one active with the pulsed laser simulating a muzzle flash and one passive with just the background. Both these measurements were performed with identical settings (resolution 32x32 pixels). The two measurements were then combined in Matlab so a background reduction could be made. Because the active and passive measurements were made manually with a large time delay (maybe up to a minute time difference), variations are expected because of changing scene conditions. This will degrade the results, because the outdoor scene suffers from sunlight variations, turbulence and moving shadows.

An example of the signals when an outdoor reflector is pulsed with the laser can be seen in Figure 4. The data was background-subtracted and different parts or lengths of the signal (during the laser pulse) could be reconstructed to an image of the muzzle flash. If enough patterns are reconstructed during the pulse, the result will be a dark image with the brightest pixel at the position of the light source. The reconstruction was made in TVAL3 using only one iteration, thus making the process very fast.

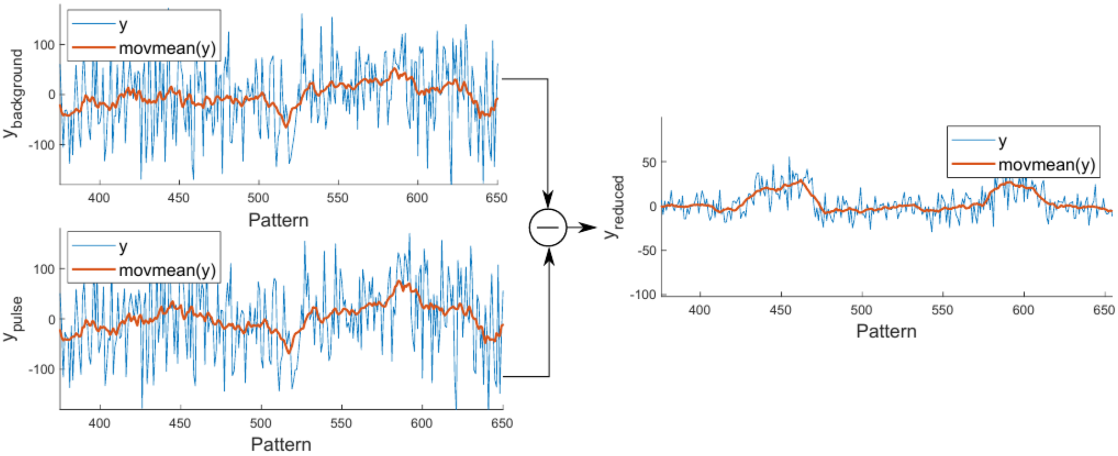

Figure 4: Background signal (top left), signal with pulses/flashes (bottom left) and the background-reduced signal (right) captured at a pattern rate of 1440 Hz. In the background-reduced signal most of the image information is removed, leaving only the data of the two 25 ms simulated muzzle flashes and some noise. The blue curve is the measured signal and the red curve shows the moving average.

In Figure 5, the restored 32x32 image (using 20 patterns) of the simulated muzzle flash is superimposed in red over the outdoor scene. 20 consecutive patterns during a part of the 25 ms laser pulse are used to restore the red overlay image. The outdoor scene is also captured at 128x128 resolution (3000 patterns with a subsampling ratio of 18%), when the light source is continuously on, thus visible as a small bright light.

Figure 5: B/W image of the outdoor scene at 128x128 pixel resolution, reconstructed using a subsampling ratio of 18%. The Ø7 cm reflector, seen as a bright dot when the laser is continuously on, is mounted on a tree at 350 m range. The red overlaid image of the simulated 25 ms muzzle flash is reconstructed to 32x32 pixel resolution using 20 consecutive patterns (during a pulse) and illustrates the capability to detect and localize the flash at the same position as the reflector (ground-truth).

Tests were made to evaluate the number of patterns needed to locate a small light source. During the tests, the laser was continuously illuminating the reflector (in the outdoor scene) and thus a wide range of pattern combinations (different sections of the signal) could be reconstructed to test if the strongest pixel in fact was the light source for each individual image. From the measurements, 500 patterns were analysed and M (<40) different consecutive patterns were used to reconstruct a large number of images. The reconstruction was made in TVAL3 using one iteration. The results from the experiments are presented in Figure 6. As can be seen, the probability to locate the flash is almost zero below five patterns but then rises quickly and after 25 patterns reaches almost 100%. Because the patterns displayed on the DMD are random, the probability to find the light source is dependent on the specific pattern combinations during the muzzle flash.

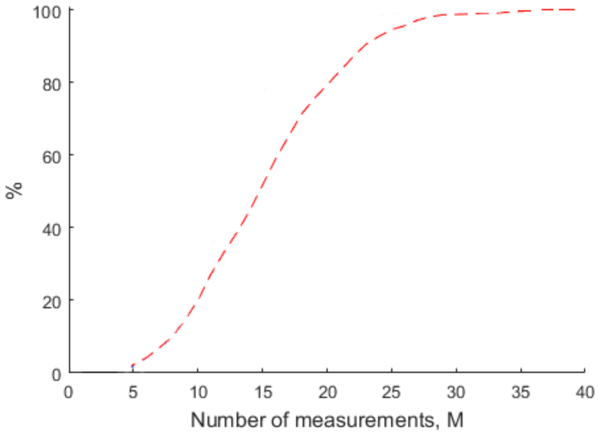

Figure 6: Probability to find the correct pixel (illuminated reflector) in the reconstructed image given M number of samples.

Finally, to illustrate the high-resolution capability of the SPC system, Figure 7 presents images of two cars at 512x512 and 256x256 pixel resolutions at subsampling ratios of 30% and 40%, respectively.

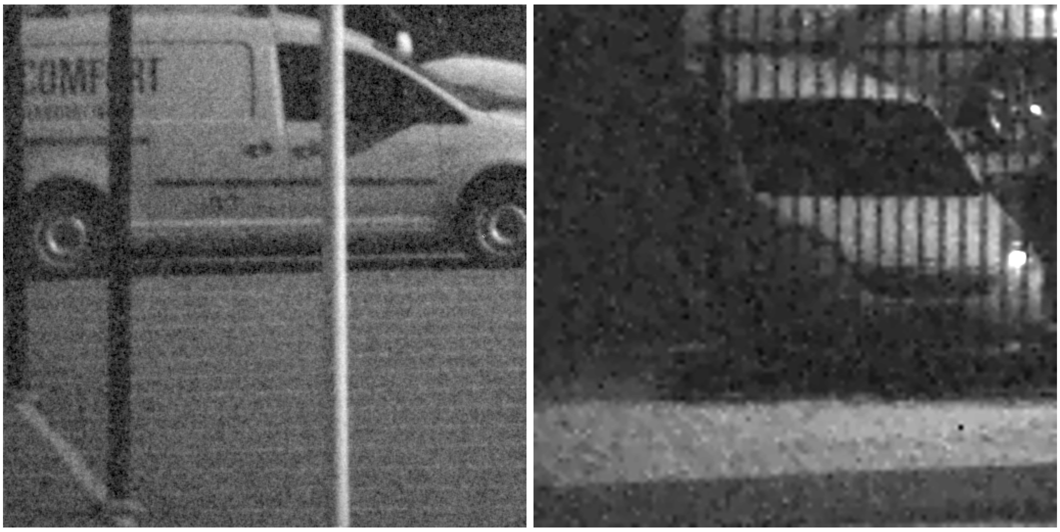

Figure 7: Two images of cars at 512x512 (left) and 256x256 (right) pixel resolutions at 350 m. Subsampling ratios are 30% and 40%, respectively. In the left image a fence can be seen in the foreground (seen as thin horizontal lines).

5.0 DISCUSSION AND CONCLUSIONS

Conventional FPA-based solutions to muzzle flash detection are challenging, due to limitations in frame rates, signal processing demands as well as storage and transmission bandwidth requirements. The sparse nature of the transient and highly localized events however suggests that CS-based approaches might be useful. Results of our initial experiments, based on long range detection of 25 ms laser pulses with our DMD-based single pixel SWIR camera, show great potential of both detection and localization of the flashes with the 1440 Hz sampling rate provided by the current DMD. A high (99%) localization probability have shown to be provided after only 25-30 samples, corresponding roughly to the pulse width of the laser and to 2-3% sampling ratio of a reconstructed image at 32x32 pixel resolution. Near-future improvements of the system will include a faster DMD with a 32 kHz sampling rate, which will provide a setup suitable for experimenting with shorter and more realistic pulse shapes as well as real gun muzzle flashes (typically of durations of 1 ms or less). Although the initial focus has been given to muzzle flash detection, it is also conceivable that the system could be used for sniper optics detection by using active CW or pulsed laser irradiation, using similar techniques as described in the paper. Detection of other transient and spatially limited events of military interest could be explosions and missile launches at longer ranges.

6.0 REFERENCES

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