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STANDOFF DETECTION OF IEDs WHILE ON THE MOVE

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ABSTRACT

ChemImage's LightGuard sensor incorporates short-wave infrared (SWIR) hyperspectral imaging (HSI) to help address the problem of standoff detection of IEDs. The sensor technology exploits uncooled focal plane array technology in combination with novel liquid crystal optics and real-time machine vision processing methods to provide high definition imagery of IED threats in highly cluttered environments. LightGuard technology has been tested successfully at speeds up to 15 mph and at distances up to 200 m for the detection of military and homemade explosives, IED command wires, EFP camouflage and disturbed earth associated with IED emplacements. A summary of validated test results will be discussed which show LightGuard technology having unprecedented detection capability, including high sensitivity and low false alarm rates which enhance vehicle survivability.

INTRODUCTION

Proliferation of improvised explosive devices (IEDs) is a growing threat to civilians, soldiers and their equipment. IEDs have been used extensively against coalition forces in Iraq and are the weapon of choice among insurgents in Afghanistan. Since the inception of combat operations, the United States Department of Defense (DoD) estimates that (as of 2006) nearly 50% of casualties in Iraq have been a result of IEDs [1]. In 2010, an estimated 57% of coalition combat deaths in Afghanistan have been caused by IEDs [2]. As the term "improvised" implies, IEDs can come in a variety of forms and settings, however all are designed to distract, delay, incapacitate and/or destroy personnel or vehicles. IEDs typically incorporate some form of explosive (military, commercial or homemade) along with an explosive charge, a detonator and an initiation system. Shrapnel generating objects or armor penetrators may be used in IEDs, as well as toxic chemical, biological and/or radioactive material. IEDs can be placed in a variety of scenarios, such as buried in the ground, vehicle-borne (car/truck bombs) or personnel-borne (suicide bombers). Because of the growing danger and the unpredictable nature of IEDs, counter-IED (C-IED) efforts are at the forefront of military forces [3].

Many existing explosive detection technologies require close proximity sensing – endangering the safety of operators, and risking damage to costly equipment. Several standoff sensors exist for the detection of IEDs. Many of these sensors, however, are laser-based systems and present a risk of blinding personnel who may find themselves in the path of the laser beam. Furthermore, most of the existing explosives detection technologies lack the ability to support autonomous, real-time, OTM architectures. This paper describes how the ChemImage LightGuard sensor has features and capabilities that provide more relevant support to the C-IED endeavor.

LIGHTGUARD SENSOR

The LightGuard Sensor is a short wave infrared (SWIR) hyperspectral imaging (HSI) system for eyesafe, standoff detection of disturbed earth, homemade explosives (HMEs), military explosives and chemicals on surfaces, as well as IED command wires and/or EFP camouflage, all of which can be associated with IEDs or IED emplacement activity. Detections may be performed with the sensor in a fixed site configuration and/or in an on-the-move (OTM) scenario.

In operation, solar radiation or external lighting illuminate a surface and photons are absorbed or reflected by the materials in the field of view, depending on their composition. A portion of the reflected photons are collected by a lens and images are generated as a function of wavelength modulated by a SWIR liquid crystal tunable filter (LCTF). The LCTF covers the SWIR wavelength range of 900-1700 nm and is coupled to an uncooled InGaAs focal plane array detector. Because the images are collected as a function of wavelength, contrast within the image is indicative of the varying amounts of absorbance, reflectance or scatter associated with the various materials present in the field of view. Additionally, each pixel in the image has a fully resolved SWIR spectrum associated with it. The resulting SWIR spectral signatures are compared to a SWIR spectral library compiled from known material signatures and trained against ambient background. Positive detections are obtained by comparing the SWIR scene to a signature library using pattern matching algorithms. This method yields a rapid, reagentless, nondestructive, non-contact method capable of fingerprinting trace materials in complex background.

The LightGuard SWIR HSI sensor addresses the need to operate in a stand-off configuration allowing for target-to-sensor distances of up to 200m. Through use of a customized SWIR zoom lens, LightGuard facilitates wide area surveillance capability as well as high magnification targeting for local area confirmation of residues on surfaces. High definition visible imaging is also incorporated in the LightGuard sensor to assist in targeting areas of interest.

Because the sensor operates in reflectance mode and explosive signatures are based on vibrational absorbance spectroscopy, sensitivity is determined by the absorbance cross section (absorptivity) of the explosive material, the noise characteristics of the detector and spatial resolution of the sensor. LightGuard has sensitivities reaching sub-microgram/cm^2 levels.

The selectivity of the LightGuard sensor is in part due to the wavelength agile LCTF. The LCTF can be tuned to any wavelength in the spectral range, giving us access to hundreds of spectral bands and thus generating a fully resolved SWIR spectrum for every image pixel. The absorption bands associated with the SWIR region of the spectrum generally result from overtones and combination bands of O-H, N-H, C-H and S-H stretching and bending vibrations. The molecular overtones and combination bands in the SWIR are typically broad, leading to complex spectra where it can be difficult to assign specific chemical components to specific spectral features. However, taking advantage of multivariate statistical processing techniques also helps to improve the selectivity of the LightGuard sensor. By applying these techniques, we can generally extract the important chemical information. The individual components of interest are uniquely identified based on their absorbance properties.

In additional to multivariate statistical processing, our algorithm development efforts have addressed the need for real-time detection. We have developed a software package known as the Real Time Toolkit (RTTK) that provides detection and identification necessary to enhance the soldier, civilian and vehicle survivability.

Additional features of LightGuard are summarized in **Table 1**. An image of LightGuard is shown in **Figure 1**.

Features	Key Technology Solutions and Benefits
Sensing Modality:	Shortwave IR (900-1700 nm; 8 nm bandpass) hyperspectral imaging
Types of Targets:	Explosive and chemical residues, disturbed earth, camouflaged EFP, command wires
Time to Detect:	< 2 seconds
Detection Range:	Exceeds 200 m (target type, concentration & CONOPS dependent)
Size:	0.07 m^3
Weight:	75 lbs
Power Required:	0.5 kW
Maturity:	TRL 7
Safety Issues:	None: Passive Sensor; eye safe; radiation safe

Table 1: Summary of LightGuard Key Features.

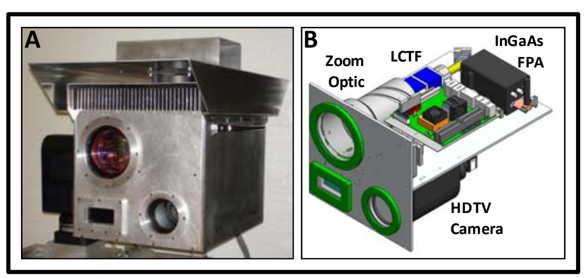

Figure 1: (A) Digital Image of LightGuard Sensor (B) Diagram of LightGuard internal components.

ACQUISITION, PROCESSING AND DETECTION

Standoff, OTM detection of IEDs involves the detection of materials associated with IEDs. These materials can include one or all of the following: disturbed earth, HMEs or military explosives, chemicals, command wire and/or EFP camouflage. We can apply different acquisition, processing and detection techniques, depending on the material we are trying to detect.

The first steps in the hyperspectral image data collection procedure involve acquiring a background image and a flatfield image. The background image provides a means to correct for instrument noise, while the flatfield image provides a means to correct for non-uniform detector response. Finally, an optical image (to provide a digital record of the target) is collected while simultaneously acquiring a SWIR hyperspectral image set to collect over a discrete number of wavelengths from 900 – 1700 nm. Generally, positive detections can be made by acquiring 10 wavelength bands or less; however in some instances a hyperspectral image covering the entire spectral range is necessary. The integration time is user controlled and can be set from 0.02 – 33.2 msec per image frame. The number of frame averages is also user controlled and for OTM applications, the number of averages is typically set to 1. A higher number of averages improves data signal to noise ratio (SNR), but slows data acquisition rates.

The following pre-processing steps are applied to the SWIR HSI dataset: The background image subtraction and the ratiometric flatfield corrections are applied as the hyperspectral images are collected. Image alignment is then applied to the HSI to correct for sensor/scene motion artifacts. Next, the reflectance image is converted to absorbance [$-\log(R/R_o)$] to provide a linear relationship between absorption and concentration according to Beer's Law. Finally, Standard Normal Variate Transform (SNVT) is applied to normalize the data and correct for light scattering effects.

Once the images are pre-processed, the data is classified using a Partial Least Squares Discriminant Analysis (PLSDA) model. PLSDA is a multi-variate statistical approach, performed to sharpen separation between classes. PLSDA is a supervised approach, however, and does require knowledge of the classes to be separated. With PLSDA, a model is built using a training set of data. Each piece of data in the training set is categorized as a particular class. Probabilities for each class category are determined by applying PLS regression and discriminant analysis to the training data. The distinction for unknown data is therefore predicted based on that which demonstrates the highest probability for a particular class. One main advantage of PLSDA is that once the models are built, classification is fast. The variance captured by PLSDA is useful in separating class and is generally ignored when it occurs within a class.

In some cases, we find it is not necessary to collect a hyperspectral image dataset; rather, two discrete wavelengths are collected. The two images are then divided and an intensity threshold and/or area threshold is applied. This provides a means to binarize the image. Detections are made based on the threshold setting for the various components.

In either case of data collection and processing, the RTTK software package facilitates real-time detection of IEDs while OTM.

RESULTS AND DISCUSSION

ChemImage has previously generated significant interest in our standoff optical sensor technology, in large part due to the successful demonstrations of these technologies as part of Government-sponsored field trials. In one particular field trial, approximately 120 total emplacements were blindly distributed across 8 test sites (approximately 15 emplacements / site). Each test site consisted of approximately 1.5 km of paved and unpaved roadway. The majority of the emplacements contained urban clutter, ordnance and/or explosive residue, which were considered IEDs. Seventy nine (79) emplacements were evaluated with all emplacements found. Additionally, 95% of IED targets (59 out of 62) were detected, even when line of sight (LOS) was not always achieved. Command wires, disturbed earth and pressure plates were readily detected using the CONDOR-ST, Gen 2 Sensor. The CONDOR-ST is a SWIR HSI system and was a precursor to our more refined LightGuard sensor. **Figure 2** shows data collected at a test site in 2008 from the CONDOR-ST sensor, mounted on a vehicle and operating at an elevation of approximately 3 m off the ground and at a standoff distance of 50 m. This data reveals detection of disturbed earth, along with command wire and EFP foam camouflage in one scene.

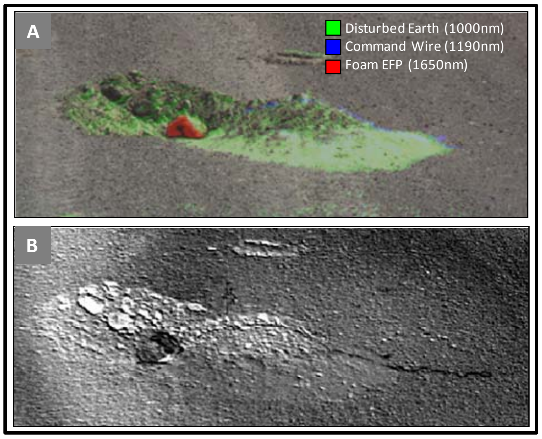

Figure 2: (A) The detection image of a scene containing disturbed earth, command wire and foam EFP. Disturbed earth detection is shown in green, the blue line shows the detection of command wire while the detection of foam EFP is shown by red; (B) The SWIR absorbance image extract collected from the scene.*

During a particular government-sponsored field test, ChemImage demonstrated its CONDOR-ST technology as a best in class standoff sensor, which was a key contributor to the successful blind trial detections of IEDs. As a result of the success with this particular field test ChemImage was requested to participate in an accelerated disturbed earth detection project in August 2009. In disturbed earth detection project, ChemImage's SWIR sensor operated in an OTM configuration, traveling at 3, 5 and 7 mph, respectively. **Figure 3** shows an example of disturbed earth detection at a 70 m standoff distance. In addition, ChemImage demonstrated stand-off detection of disturbed earth at 200 m .

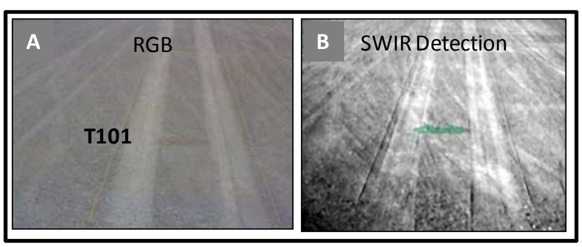

Figure 3: (A) Digital image of target 101; (B) Detection image of target 101. The green marking indicates the location of disturbed earth.*

Figure 4 illustrates the detection of ammonium nitrate (AN) explosive residue on the ground while OTM. Detections were made at a 50 m standoff distance.

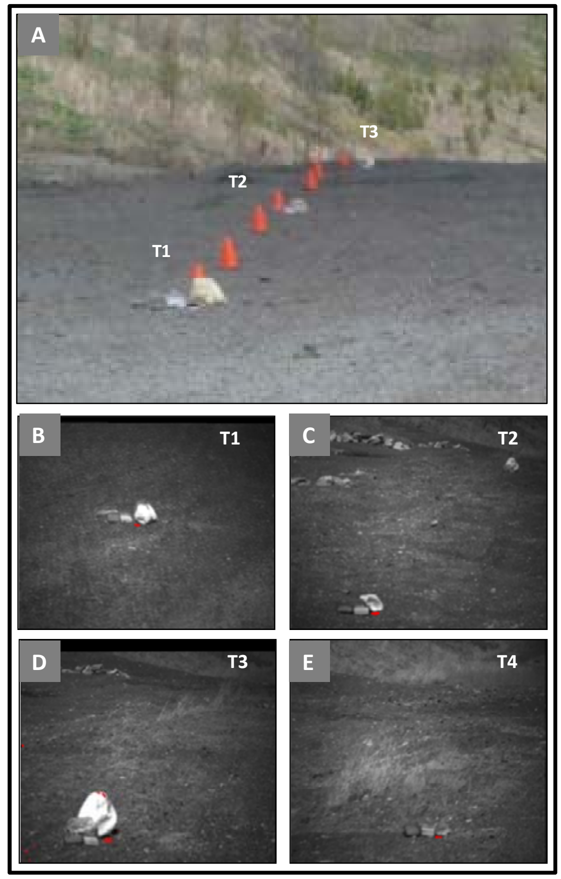

Figure 4: (A) Digital Image showing the location of AN targets; (B-E) Detection images associated with the AN targets. The red markings indicate an AN detection.

In independent evaluations, our LightGuard sensor has also demonstrated capability to detect HMEs on vehicle surfaces as well as on human skin and clothing, possible indicators of vehicle-borne IEDs and personnel-borne IEDs, respectively. The results of these detections are illustrated in the figures below. **Figure 5** shows the detection of an AN handprint on the surface of a vehicle. This detection was made outside during a snow storm. **Figure 6** shows the detection of AN on skin after a person handled the AN material and finally, **Figure 7** shows the detection of AN residue on a person's shoe as the individual is moving through the scene. The four individual frames in this figure illustrate the SWIR hyperspectral image frame progression.

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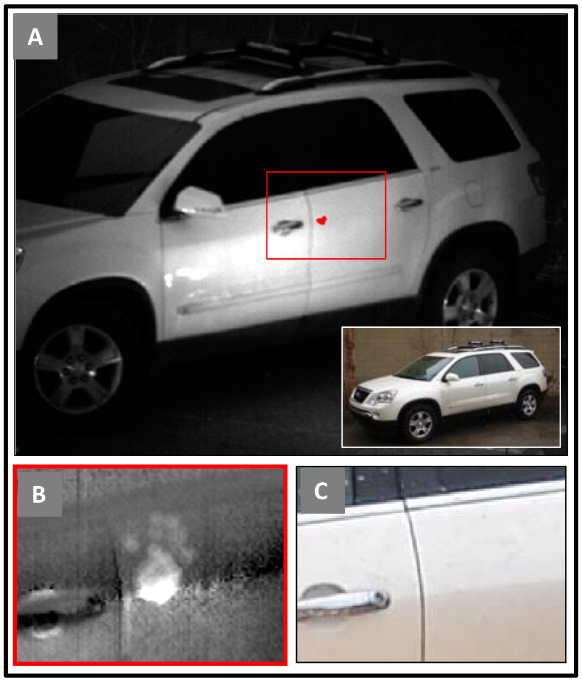

Figure 5: (A) shows the detection image of an AN handprint on a car door. The detection is characterized by the red marking; (B) shows the zoomed in absorbance image of the AN handprint; and (C) shows a digital image of the car door where the handprint is located.

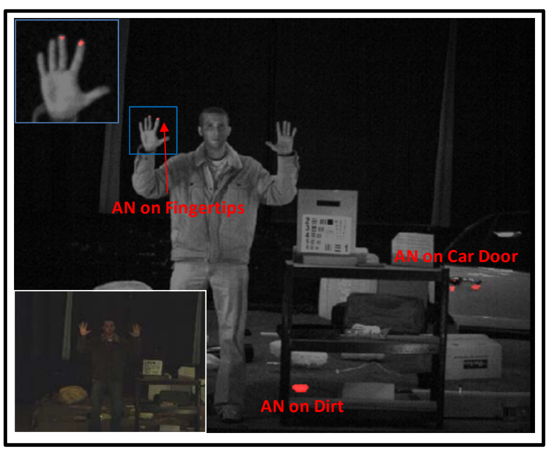

Figure 6: AN detection on fingertips, on a car door and on dirt.

Figure 7: AN detection on a person's shoe, moving through the scene.

SENSOR FUSION

Raman HSI has also been evaluated as an IED detection tool. While the presentation of the Raman results is outside the scope of this paper, we have demonstrated that the Raman method and the SWIR method, operating alone each have utility in the area of IED detection. However, when these two modalities are combined we achieve a more complete solution. The sensor fusion approach involves the following steps:

1. Generate a SWIR score image by applying the appropriate pre-processing steps and performing either a division between the two frames, or by applying a PLSDA model to the SWIR input image. The PLSDA model is built by selecting the appropriate training set of data, incorporating both the training set of spectra of the material of interest class as well as background class spectra.
2. Generate a Raman PLSDA score image, applying the PLSDA model to the Raman input image. The PLSDA model is built by selecting the appropriate training set of data, incorporating both the spectra of the material of interest class as well as background class spectra.
3. These two resultant score images are fused in a Bayesian fusion. This method utilizes a "classify then fuse" approach. Note that an image weighted approach to the fusion may also be applied.

The example below (**Figure 8**) shows how sensor fusion improves the probability of detection (P_D) of AN over each method operating independently. By employing sensor fusion, a P_D gain of 7% is achieved over the individual Raman measurement and a gain of 16% is achieved over the individual SWIR measurement.

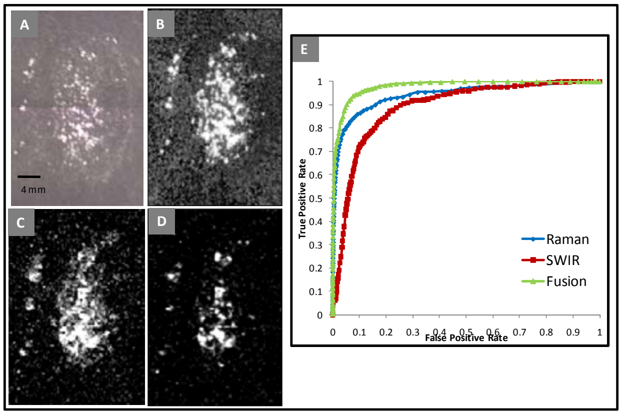

Figure 8: Example of Sensor Gain improvement. (A) shows the RGB image of the AN fingerprint; (B) shows the 1570 nm SWIR image; (C) shows the fusion image; (D) shows the 1040 cm^{-1} Raman image; and (E) shows the ROC curves associated with the Raman P_D (blue), SWIR P_D (red) and the fusion P_D (green).

FUTURE WORK

While the scenarios described in the previous sections have involved the LightGuard sensor (or previous generation SWIR sensors) mounted to a fixed platform or a manned vehicle, our future research involves mounting an OTM detection system to an Unmanned Ground Vehicle (UGV), specifically the TALON robot shown in **Figure 9**. This system fuses SWIR and Raman HSI into one sensor for standoff, OTM IED detection. This sensor is known as STARR (Shortwave-infrared Targeted Agile Raman Robot), and takes advantage of the improvement in P_D that is achieved when sensors are fused.

Figure 9: Conceptual design showing the STARR sensor mounted to the TALON robot.

This design involves important improvements to current sensors, as it incorporates agile laser scanning which helps to facilitate targeting, improved area search rates and matched SWIR & Raman fields of view.

CONCLUSIONS

Detection of IEDs at standoff distances, while on the move is an important problem to address. ChemImage's LightGuard SWIR HSI Sensor helps to address this problem and has demonstrated unprecedented detection capability at numerous government managed and independently conducted field trials. LightGuard's high sensitivity and low false alarm rates provides more reliable results, which enhances vehicle survivability and ultimately has the power to save the lives of soldiers and civilians.

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