Advanced shortwave infrared and Raman hyperspectral sensors for homeland security and law enforcement operations

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ABSTRACT

Proliferation of chemical and explosive threats as well as illicit drugs continues to be an escalating danger to civilian and military personnel. Conventional means of detecting and identifying hazardous materials often require the use of reagents and/or physical sampling, which is a time-consuming, costly and often dangerous process. Stand-off detection allows the operator to detect threat residues from a safer distance minimizing danger to people and equipment. Current fielded technologies for standoff detection of chemical and explosive threats are challenged by low area search rates, poor targeting efficiency, lack of sensitivity and specificity or use of costly and potentially unsafe equipment such as lasers. A demand exists for stand-off systems that are fast, safe, reliable and user-friendly.

To address this need, ChemImage Sensor Systems™ (CISS) has developed reagent-less, non-contact, non-destructive sensors for the real-time detection of hazardous materials based on widefield shortwave infrared (SWIR) and Raman hyperspectral imaging (HSI). Hyperspectral imaging enables automated target detection displayed in the form of image making result analysis intuitive and user-friendly.

Application of the CISS' SWIR-HSI and Raman sensing technologies to Homeland Security and Law Enforcement for standoff detection of homemade explosives and illicit drugs and their precursors in vehicle and personnel checkpoints is discussed. Sensing technologies include a portable, robot-mounted and standalone variants of the technology. Test data is shown that supports the use of SWIR and Raman HSI for explosive and drug screening at checkpoints as well as screening for explosives and drugs at suspected clandestine manufacturing facilities.

Keywords: hyperspectral imaging, standoff detection, sensor, residue, explosives, drugs, standoff, Raman, shortwave infrared

1. INTRODUCTION

Explosive, chemical and narcotic threats to civilian and military personnel continue to be problematic even in the homeland. From 2003 to 2011, 134 accidents with home-made chemical bombs were reported by the Center for Disease Control[1][1] among 15 participating states. In six months before Boston marathon bombing, between October 2012 and March 2013, there were 172 improvised explosive devices (IEDs) reported in the United States.[2] All but five of these reports involved explosives enthusiasts, rather than terrorists.

Law enforcement and military need to identify threats by detecting the chemical components used in explosives manufacturing. Explosives include a variety of chemical compounds [3] such as nitro-organics, peroxides or nitramines – each presenting unique detection challenges. Thus, a universal explosive detector is rarely possible or practical. Some existing technologies require close proximity for detection, bringing an inherent risk to the operator. Others have to use laser radiation for excitation that can expose the operator and bystanders to potential eye and skin damage. These technologies also tend to cover small areas, sometimes as small as a focused laser spot, creating a need to make multiple measurements in order to scan an area.[4] Thus, many of the existing technologies are very time consuming, making them impractical for autonomous, real-time detection applications.

The ability to detect threats from a safe distance positively impacts safety and prevents casualties. To address this need ChemImage Sensor Systems (CISS) has been developing short-wave infrared (SWIR) hyperspectral imaging (HSI) and Raman HSI approaches for detection of military and home-made explosives, and chemical warfare agents. Other applications of remote sensing include the application of HSI in forestry, agriculture and emission control. HSI combines spectroscopy and digital imaging by allowing visual representation of chemical contrast. In this paper, we describe

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several applications of the CISS' SWIR-HSI and Raman sensing technologies to Homeland Security and Law Enforcement.

2. HSI TECHNOLOGY

Hyperspectral imagers are capable of providing both spatial and spectral information from a scene. Such systems can produce three-dimensional images (two spatial dimensions and one spectral dimension) called hypercubes.. Unique spectral signatures containing rich chemical information may be obtained for each pixel within the scene. In general, HSI systems include a camera with appropriate optics, a wavelength-selecting element, and a computing platform for data acquisition of discrete spectral bands.

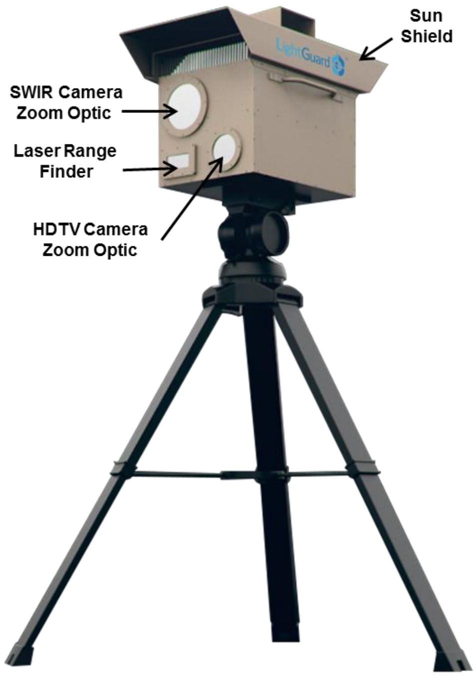
SWIR HSI operates in the short-wave infrared region (SWIR), specifically from 900-1700 nm. Materials in the scene either absorb or reflect incident sunlight (or a similar broadband radiation) depending on their composition. In order to acquire spectral information, CISS uses a liquid crystal tunable filter (LCTF), a birefringence interference imaging spectrometer composed with high throughput and high out-of-bandpass rejection efficiency. The LCTFs have a fast tuning response (~ 50 ms) and are capable of yielding spatially-resolved SWIR signatures of an entire scene in a matter of seconds. These hyperspectral spectrometers are typically coupled to an uncooled InGaAs focal plane array or similar detector. A laser or any similar radiation-based source is not required for SWIR HSI, so the technology is capable of monitoring people or any other biological entities with insignificant radiation hazard concerns.

2.1 LightGuard™ Hyperspectral Imager

CISS has developed a SWIR HSI passive LightGuard™ sensor that can detect a target using only sunlight or other forms of broadband illumination. LightGuard conducts wide-area surveillance with high target specificity by making threat detections by comparing each SWIR scene to a signature library in real time. Figure 1A shows a LightGuard sensor mounted onto a tripod. The sensor head is equipped with a sun shield to eliminate glare directly onto the camera lens. The sensor has an extensive range pan and tilt function, expanding its already wide area coverage. The sensor is equipped with a zoom lens, letting the operator closely investigate potential targets from standoff distances up to 50m or more (depending on the size of the target and amount of material present). In addition, the LightGuard sensor has a high-definition RGB camera for visual confirmation of potential threats. Using graphics processing units (GPUs) and parallel data processing allows the system to achieve detection results fast enough to make detections in real time. LightGuard sensor is geared towards entry and/or traffic control point vehicle check points, personnel screening, border check point surveillance, examination of hazardous materials and clandestine lab examination.

A military variant of LightGuard™ technology recently completed a two year Operational Assessment in Kuwait and Afghanistan examining vehicles and personnel both at Entry Control Points (ECP) and Border Crossing Points (BCP). This deployment has led to successful detection and interdictions of contraband smuggling and/or evidence of Home Made Explosives (HME) manufacturing and trafficking. An example of standoff detection in a vehicle checkpoint scenario is shown in Figure 2. The left image shows a scene as the checkpoint operator would see from a 10m standoff distance. The SWIR detection image at the right shows the explosive residue that was detected on the vehicle car door. Since RGB imagery is collected simultaneously with and can be matched to the SWIR field-of-view, the additional image date provides further documentation as well as situational awareness to the operator. Technical characteristics of LightGuard sensor are shown in **Table 1**.

The LightGuard system has repeatedly shown best in class detection of explosives on surfaces in real-time at numerous government-sponsored test events, detecting known HME and precursor components. It eliminates the danger associated with close proximity due to stand-off operational configuration (7-50 m nominally, with demonstrated capabilities up to several kilometers). The powerful variable zoom lens allows for both wide-field and close up operation with inspection time on the order of 10 seconds per vehicle/person.

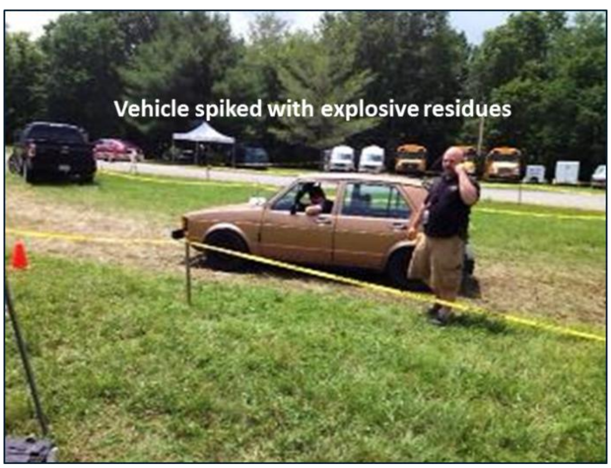


A)

B)

Figure 1. A) Solid model rendering of LightGuard™; **B)** Solid model rendering of VeroVision™

A)



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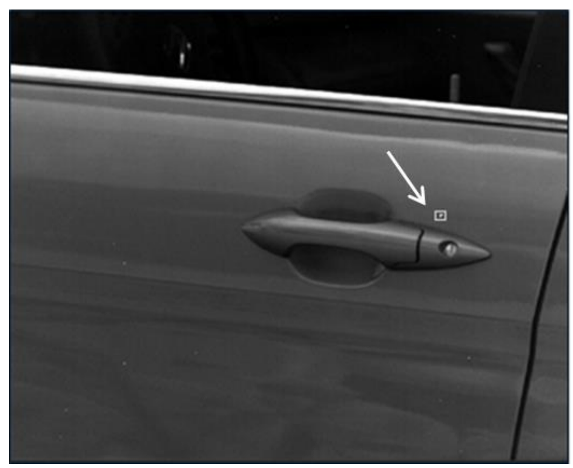


Figure 2. Example vehicle checkpoint scenario. **A)** Digital Image of a vehicle spiked with explosive residue; **B)** SWIR detection image shows a fingerprint transfer of an explosive. An arrow was added to the SWIR image to emphasize the detection.

2.2 Portable Hyperspectral Sensor (VeroVision™)

While LightGuard is suitable for long-term standoff checkpoint type applications, a demand exists for smaller, portable, more cost-effective HSI systems that enable indoor and outdoor operation. Typical applications for such systems include standoff detection of illicit drugs, explosive residues and other chemical threats. To address this need, CISS developed and continuously improved a portable molecular surface analyzer called VeroVision.[8] VeroVision is a smaller and simpler version of LightGuard (Figure 1B) capable of detecting the same types of targets at LightGuard, but at a short standoff distance of 1-20 m. VeroVision™ characteristics are summarized and compared to LightGuard in **Table 1**.

The VeroVision optical design efficiently collects light allowing automatic detection at low µg/cm^2 quantities of threat simulants. Single pixel detections have been demonstrated. **Figure 3** shows detections of 5 µl droplets of CWA simulants dimethyl methylphosphonate (DMMP) and methyl salicylate (MES), at a 2 m standoff distance. VeroVision has been demonstrated to detect vehicle and person-borne explosives, illegal substances and adulterated food.

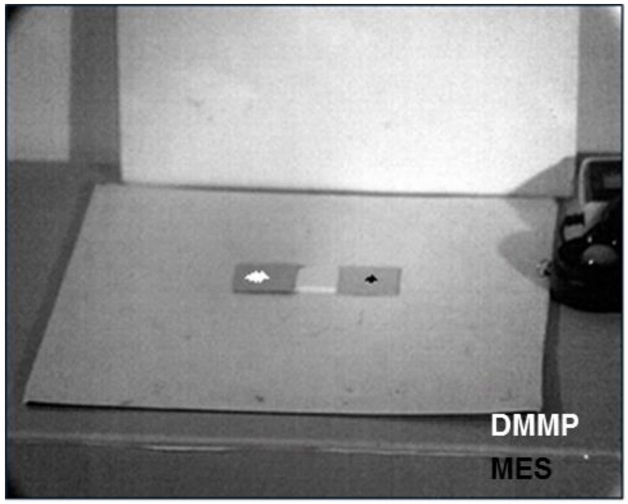


Figure 3. Detection of 5µl depositions of DMMP and MES at 2 m standoff.

Table 1. Technical Characteristics for LightGuard and VeroVision™ HSI sensors.

Device / Features	**LightGuard™**	**VeroVision™**
Weight (Sensor Head)	123 lb (Sensor Head) 124 lb (Processing Computer/Power Unit)	8.3 lb (Sensor Head)
Size (Sensor Head)	18'L x 12.8"W x16"H	14.2" x 7.9"W x 5.5"H
Angular field-of-view	20.8° (Min Zoom) 5.1° (Max Zoom)	24.0° degrees (wide angle) 12.0° degrees (narrow angle)
Horizontal viewing region at 10m standoff	3.4m x 2.74m (Min Zoom) 0.8m x 0.64m (Max Zoom)	3.5 x 2.8 m (wide angle) 1.7 x 1.4 m (narrow angle)
Standoff Distance	7 - 50 m	0.5-20m
Power Supply	90-240 VAC 50-60 Hz	90-240 VAC 50-60 Hz
Power (Excluding Lights & ODU)	435 W	230 W
Usage	Tripod or Vehicle Mounted	Tripod mounted
Hardware:	Motorized tripod, GPS, LRF, wireless communication, continuous zoom/focus on RGB and SWIR cameras **Optional:** Auxiliary lighting for low light operation	**Optional:** Motorized tripod, GPS, LRF, wireless communication, battery operation; auxiliary lighting for low light operation
Supplemental Lighting:	External stationary lights	External and Clip On lights
Types of Targets	Explosives, Chemical Threats, Foodborne Threats & Illicit Drugs	Explosives, Chemical Threats, Foodborne Threats & Illicit Drugs
Targets detected in 10 sec	Multi-Target detection: 5 materials / material classes	Multi-Target detection: 5 materials / material classes
Detection Algorithm	Automated Local Threshold; Persistence; Available Morphological Filters	Automated Local Threshold; Persistence; Available Morphological Filters

VeroVision™ has the following additional optional features: (a) the capability to remotely direct the SHU using a motorized tripod-mounted PTU, (b) an integrated GPS system to provide the location of the sensor system, (c) a laser range finder (LRF) to provide target range information, (d) snap-on optics to enable greater flexibility in detections and improved image quality, (e) WIFI capability for remote, wireless operation, and (f) clip-on supplemental lights that may be attached to the tripod frame for indoor work or low light level conditions.

2.3 Robot-mounted Hyperspectral Sensor (STARR)

Explosive Ordinance (EOD) technicians are trained to identify and remove the threat of IEDs. A standoff mobile sensor with fast area search can give these technicians a greater understanding of the threat while keeping them at a safe distance. Such system needs to offer high sensitivity and specificity along with a wide surveillance area.

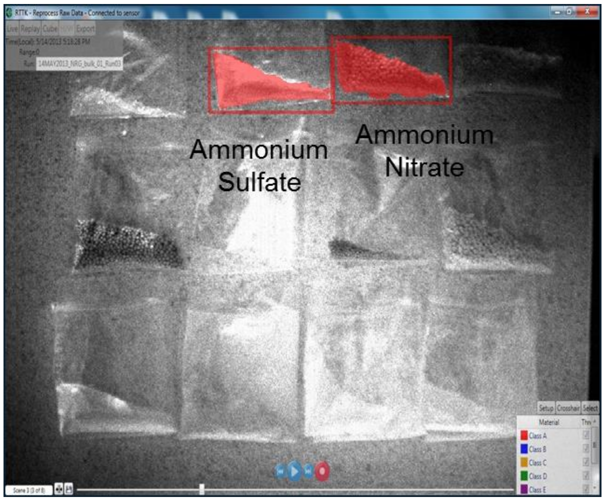
To meet the needs of EOD technicians, CISS developed a multi-hyperspectral sensor system called STARR[9] (Shortwave-Targeted, Agile Raman Robot) (shown in **Figure 4)**. The SWIR HSI offers wide-area surveillance and autonomous, real-time threat identification of surface residues while the Raman HSI system is used to make high-specificity confirmation measurements of the SWIR-identified threat. Each sensor in the system was constructed to work in a standoff distance range of 1-3 meters. STARR is mounted onto a TALON UGV (unmanned ground vehicle) to give it greater mobility. Once a threat is identified in the SWIR HSI, the user can simply click on the threat identification and the STARR sensor's pan/tilt unit will position the Raman laser onto the threat. Once positioned, STARR will automatically trigger the laser to collect 30 laser pulses. When finished, the pan/tilt unit will return to its previous position so the user can continue analyzing the scene without having to make any adjustments. It is controlled wirelessly through an 802.11n link, allowing the operator to remain at a safe distance.

The Raman HSI sensor allows daylight outdoor operation based on gated intensified charge-coupled device (ICCD) acquisition of Raman signal in the presence of ambient lighting with a 532 nm pulsed laser excitation (5 mJ/pulse, 20 Hz repetition rate). To obtain Raman hyperspectral imagery, the sensor utilizes a fiber array spectral translator (FAST) bundle composed of 96 individual fibers. With FAST, Raman light collected from the scene is focused on the 2-dimensional proximal end of the fiber bundle. The distal end of the FAST bundle is drawn into a linear array of fibers and inserted into the entrance slit of a dispersive spectrometer. The 2D → 1D configuration allows the individual fibers to be spatially resolved at the detector, yielding 96 spatially distinct spectra in a single acquisition. All 96 spectra are run through a PLSDA (partial least squares discriminate analysis) database of Raman signatures to give confirmation of the presence of a threat.

Figure 4. STARR sensor during field testing.

Figure 5 demonstrates benefits of thetwo complementary HSI sensors. When operating SWIR HSI in real time mode, materials are grouped into classes based on their chemistry. **Figure 5A** shows the SWIR HSI detection image for ammonium nitrate and ammonium chloride among other chemicals. While ammonium nitrate is considered a threat precursor, ammonium chloride is not. **Figure 5B** shows the unique Raman spectra for each material. After running obtained Raman spectra through a PLSDA database, the ammonium chloride is not confused for a threat and ammonium nitrate presence is confirmed. Incorporating Raman HSI gives the user greater specificity than using SWIR HSI alone.

Testing of the STARR system has shown the ability of the system to provide wide-area, real time target identification (with SWIR HSI) and confirmation (with Raman HSI) in a mobile, ruggedized form. STARR was able to make threat detections on a number of substrates, including car doors and as mixtures in dirt, and at standoff distances up to five meters.



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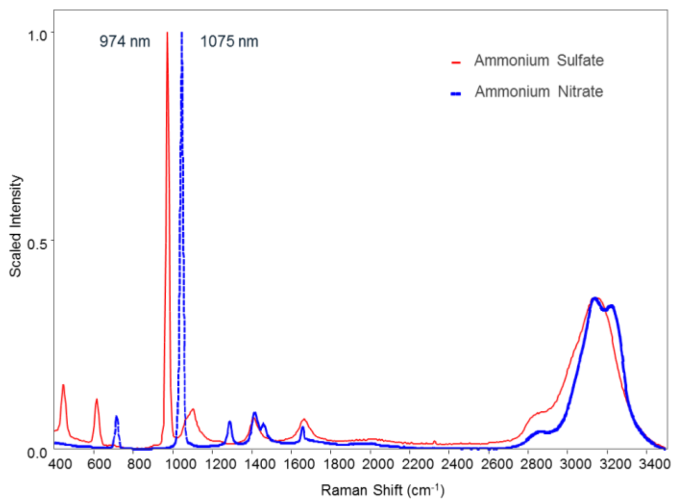


B.

Figure 5. Raman HSI as a complement to SWIR HSI. A) SWIR HSI detection of ammonium nitrate, a threat, and ammonium sulfate, which is not. B)The spectra, acquired with the Raman HSI sensor, show a distinct difference between the two compounds.

2.4 CISS Software

CISS uses a highly sophisticated software package called Spectral Kitchen™ for autonomous detection of targets in real time. Spectral Kitchen is a distributed real-time data acquisition and processing system that detects the presence of materials based on pre-configured spectral "recipes". The recipes specify a collection of wavelengths at which spectral images are captured, as well as the processing steps to perform. To make processing efficient and fast to meet real time detection standards, CISS software uses Microsoft Task Parallel Library (TPL) for concurrent processing. TPL

Dataflow organizes the processing of data so that each task runs as soon as the data is available. Apache Thrift and ZeroMQ assist communication between nodes on the system. Our Windows-based software can communicate with both a Windows-based or a Linux based hardware.

An important aspect of the Spectral Kitchen software is the automated detection algorithm that automatically sets localized detection thresholds based on local signal-to-noise ratio. This algorithm allows residues of varying concentration to be detected under variable lighting conditions without operator interference. Glare and shadow detection filters reduce false alarm associated with light or dark parts of the images. In addition, a persistence algorithm further reduces false alarms that result from incidental target motion and instantaneous, non-persistent detections.

Library “recipe” generation is accomplished in three short steps. First, a full hypercube is collected on known materials of interest. Second, the user identifies ground truth for objects in the imagery. Finally, the software processing algorithms analyzes the data and generates a rank-ordered list of best wavelengths for detecting materials of interest. These recipes are then turned on in the software at the user’s discretion. This flexibility allows tailored detection recipes for various combinations of targets and backgrounds.

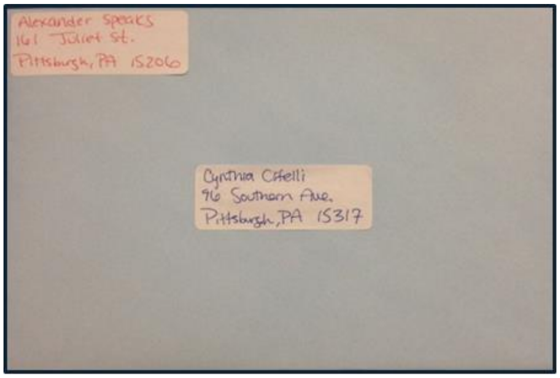
An important feature for the end user is the ability for the multi-target detection. Each collection of individual frames is processed and composited into a scene, where the detected materials of interest are highlighted in colors corresponding to different threats. For example, LightGuard and VeroVision can detect 5 classes of materials (consisting of 25 end-members) in < 10 sec. More materials may be selected for simultaneous detection, but with additional time to acquire / process the data.

Spectral Kitchen™ software has a flexible configuration for easy library updates, switching between applications and sharing libraries. It also includes the ability to create a proprietary library to expand application of SWIR HSI sensors to other fields including forensic, narcotics, food contaminants and illegal drugs screening.

3. ILLICIT DRUG SCREENING IN MAIL

Another application of SWIR HSI is screening for illegal drugs in articles of mail. Drugs being smuggled into prison in greeting cards,[10] children’s drawings[11] or books is a growing problem. Current mail screening systems are often inefficient and require manual screening of the each piece of mail. Any physical anomaly, including glitter, crayon drawings or a lipstick kiss, renders a piece of mail "suspicious" and the mail is returned to the sender. Previously, we have reported a successful detection of suboxone in presumed artwork using a VeroVision imager.[12]. Based on VeroVision CISS developed a dedicated Mail Screening System to detect drugs and common cutting agents entering a facility through the mail.

VeroVision Mail Screening system uses SWIR radiation in combined transmission /reflectance mode to detect illegal substances inside envelopes, paper, stamps and stickers and through ink, crayons, watercolors and colored pens. The detection is presented in a simple user interface. Once a suspicious item is detected, a presumptive identification of the materials is accomplished by matching the target spectrum against a spectral library database of illegal substances. A detection report is generated in correspondence with the facility requirements. **Figure 6** shows an example of detection of illegal substance hidden behind an envelope sticker without opening the letter or altering it in any way. The VeroVision™ Mail Screener allows fast screening of mail items by corrections officers in a platform that requires less than 1 hour of training.

A. 

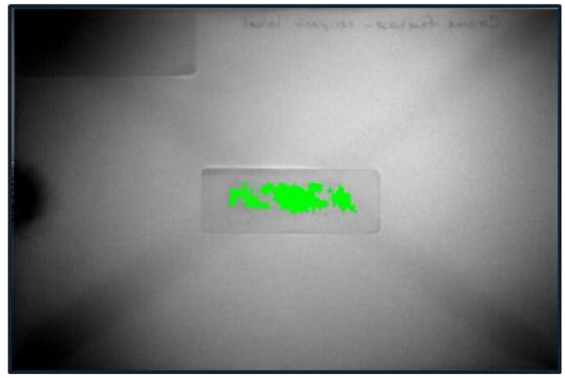
B. 

Figure 6. Digital photograph (A) and SWIR HSI detection image (B) demonstrating VeroVision™ prison mail screening application of an envelope for illegal substances.

4. CONCLUSIONS

ChemImage has developed a variety of SWIR HSI platforms with demonstrated capabilities for making autonomous detections in real time. The incorporation of liquid crystal tunable filters and ChemImage-developed detection algorithms provides SWIR HSI the adaptability to conform to a variety of explosive, narcotic and chemical threats. Variants of the technology include portable, robot-mounted and standalone sensors - each providing added safety to operators and equipment by enabling operation at standoff distances.

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6. LEGAL NOTICE