R2-C.2: Multiplexed Mid-Infrared Imaging of Trace Explosives

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II. PROJECT DESCRIPTION

Explosive residues leave distinct infrared “signatures” that can be detected by illuminating the residues with infrared light. While many scientists have studied these signatures, no technology is readily available that will allow for imaging and detection of the residues in real-world systems.

Project R2-C.2 developed technology platforms for low-cost and sensitive imaging of explosive residue signatures. This was done by developing semiconductor fabrication techniques to enable commercial infrared (IR) laser arrays to be used as compact illumination sources. Intellectual property for this process has been licensed to Department of Defense contractor, Indiana Integrated Circuits. This project also developed new chemical residue imaging platforms leveraged with off-the-shelf and low-cost infrared cameras for detection of explosives. These low size, weight, power, and cost (SWAP-C) systems were integrated into the Army Research Laboratory’s (ARL’s) electromagnetic environmental sensing and detection platform. In integrating the IR imaging system, a new distributed sensing/coordination/analysis system was implemented to allow for any generic distributed sensor system to collect data which could then be processed either remotely or on board as necessary. The IR imaging platform was then implemented with the on-board computing and communication system for aerial drones for remote, distributed detection. To overcome the increased noise from using low SWAP-C devices, a convolutional neural network was implemented to quickly denoise IR images and a new machine-learning technique was developed to identify chemical signatures by both the spectroscopic absorption and thermal time constants of the chemical film. Both of the new analysis techniques were integrated into the new distributed sensor network communication model.

Applications for these technologies include the incorporation of both the laser module and imaging systems into a variety of screening locations. Portable (deployed with security personnel), fixed (e.g., integrated with document scanners, cargo/luggage processing), and remote (e.g., unnamed aerial vehicle distributed sensor networks) platforms are being developed to both quickly identify potential threats and to aid in the detailed diagnosis of potential threats.

A. Project Overview

The overall goal of this project is to develop technology to enhance the ongoing work of the ALERT Center of Excellence by developing mid-infrared (MIR) laser-based imaging platforms capable of remote, distributed imaging and sensing of explosive residues.

A.1. Aims

- Development of low SWAP-C (size, weight, power, and cost) optical sources and imaging systems for spectroscopic imaging of explosive films.
- Integration of MIR imaging systems with remote, distributed electromagnetic sensing platforms (e.g., aerial unmanned vehicle platforms).
- Development and evaluation of novel statistical and machine-learning techniques to overcome the limitations of using low SWAP-C (i.e., noisy) detection systems for hyperspectral explosive residue imaging. The techniques will be compatible with the low-computational power integrated MIR imaging systems developed above.

A.2. Realized End-State

- A new wafer-scale laser-array to beam-combining waveguide fabrication technique was developed that demonstrated record array-to-array coupling between two MIR waveguide chips. This can be used to combine arrays of spectroscopic sources (such as those developed by ALERT partner Pendar Technologies) as well as applications in IR scene projection for other homeland security enterprise (HSE) and DoD applications. The IP is patented and licensed to DoD contractor, Indiana Integrator Circuits. This work answers the research question, “how do you combine arrays of MIR lasers, each with a different emission wavelength, into a module with a single emission output location?”
- For the first time, low-cost, commercial, uncooled vanadium oxide bolometer focal plane arrays (FPAs) were characterized for spectroscopic imaging of chemical films. The published results showed that these low SWAP-C imaging systems can achieve the signal-to-noise ratio (SNR) required for hyperspectral imaging with frame rates faster than 1 frame per second. This work answers the research question, “can newly available, off-the-shelf, low SWAP-C MIR imaging systems be capable of quantitative spectroscopic imaging?”
- MIR image acquisition, analysis, and distribution was implemented on board the computing and communications hardware for remote aerial vehicles.
- A client, broker, subscriber networking framework was developed and demonstrated for the low SWAP-C MIR imaging systems as part of the Icarus distributed sensing software platform developed by ARL’s Electronic Warfare (EW) group (Sensors and Electron Devices Directorate). To integrate the system, we improved the systems bandwidth and network latency to allow for streaming of real-time data to a centralized broker. The architecture allows for parallel analysis and chains of sequence of analysis across multiple cameras using real-time data. Distributed analysis of the data (spectroscopic imaging, denoising, and machine-learning classification) was carried out on remote servers as well as on-board systems.

- Hyperspectral imaging of high energetic material films and improvised explosive device (IED) precursors was demonstrated using the low SWAP-C imaging platforms. Detailed noise analysis was conducted to develop new denoising models required to improve low SWAP-C imaging performance.
- Noise analysis of the low SWAP-C imaging platforms found non-Gaussian noise characteristics. Previous detection algorithms assumed Gaussian distribution of pixel intensities. The project demonstrated that using generalized extreme value (GEV) distribution in a Bayesian probabilistic detection model allowed for high sensitivity chemical film detection. This work answers the research question, "does using probabilistic models using GEV distributions improve spectroscopic imaging sensitivity and performance?"
- A new machine-learning technique was developed and evaluated to classify chemical residues by their spectroscopic absorption and thermal time constant (i.e., heating and cooling rates). This enables both chemical integration ("absorption fingerprint") and characterization of the local microenvironment (thermal time constant analysis, e.g., detection of presence of plastic explosive binder). This work answers the research question, "can inclusion of thermal time constant data improve MIR spectroscopic imaging specificity?"
- Convolutional neural networks were developed and characterized for real-time denoising of MIR images. Since uncooled, low SWAP-C imaging arrays have higher intrinsic noise than the more expensive, larger, high power-consumption counterparts, we employed a new machine-learning–based technique to "restore" the SNR that was sacrificed to achieve low SWAP-C performance. This work answers the research question, "can the increase in imaging noise found in low SWAP-C cameras be improved computationally using machine-learning approaches?"
- All imaging and analysis were implemented as part of the ARL Icarus distributed sensing software platform and integrated on to the unmanned aerial vehicle computing platforms for the ARL–Notre Dame "RadioHound" electromagnetic sensing platform.

A.3. Significance and Value to ALERT and HSE

This project enhanced ongoing ALERT efforts by enabling lower cost and higher resolution imaging technology to detect signatures characterized by other ALERT projects which will be described later in this report, to provide a technology to enhance the commercial offerings of ALERT industrial partners, and to provide new low-cost spectroscopic explosive imaging platforms useful throughout the HSE. Development of the distributed sensor client/broker/subscriber platform for the ARL Icarus distributed sensor software platform has value broadly throughout the HSE and Defense enterprise by enabling easy integration of generic sensors and data analysis chains for real-time acquisition, image distribution, analysis, and data presentation to the operator and decision makers.

B. *State of the Art and Technical Approach*

MIR spectroscopic imaging has been demonstrated to be a powerful tool for trace explosives detection by several groups (e.g., [1-4]), including ALERT researcher, Professor Samuel Hernandez-Rivera of the University of Puerto Rico at Mayagüez (Project R3-C). Professor Hernandez-Rivera employs quantum cascade laser (QCL) systems that have been used to deliver high-spectral-energy-density radiation onto highly energetic materials deposited on complex substrates. Through standard preprocessing (second derivative, standard normal variate, and multiplicative scatter correction) and principal component analysis or linear regression analysis, pentaerythritol tetranitrate (PETN) and trinitrotoluene (TNT) can be detected on wood, cardboard, and aluminum substrates. Our groups have also previously characterized such signatures for Semtex, TNT, and explosive precursor hexamine on various substrates. For example, the MIR reflection "fingerprint" of Semtex is shown in Figure 1.

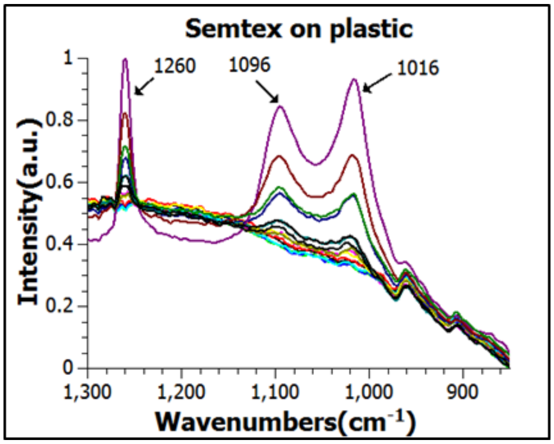

Figure 1: Demonstration of detection of Semtex film on plastic substrate. Data acquired at Notre Dame in collaboration with Professor Beaudoin, Purdue University.

While such laboratory demonstrations are interesting, the practical impact has been demonstrated by collaboration between Fraunhoffer Institutes in Germany, which have developed a trailer-based platform capable of detecting trace explosive residues at a distance of 10 m (Figure 2) [5-6]. These remarkable demonstrations showed that remote detection of explosive residue using MIR spectroscopic imaging at ~10 m is possible. However, to achieve such standoff capabilities, the platforms are large and power hungry and require expensive detector arrays.

Figure 2: Demonstration of standoff explosive residue detection from [6]. Left, image of trailer platform. Right, detection of AlN residue (yellow marks) after an improvised-explosive-device blast.

To address the need for low-cost spectroscopic arrays, we investigated using low-cost (<$250, Seek Thermal and FLIR) imaging arrays to perform spectroscopic MIR imaging of nitride films with thicknesses of 1–2 µm. Thorough noise analysis and spectroscopic imaging of nitride films were presented in [7], and example images are depicted in Figure 3. These results proved that low-cost MIR imaging arrays are capable of sensitive spectroscopic measurements of trace chemical residues.

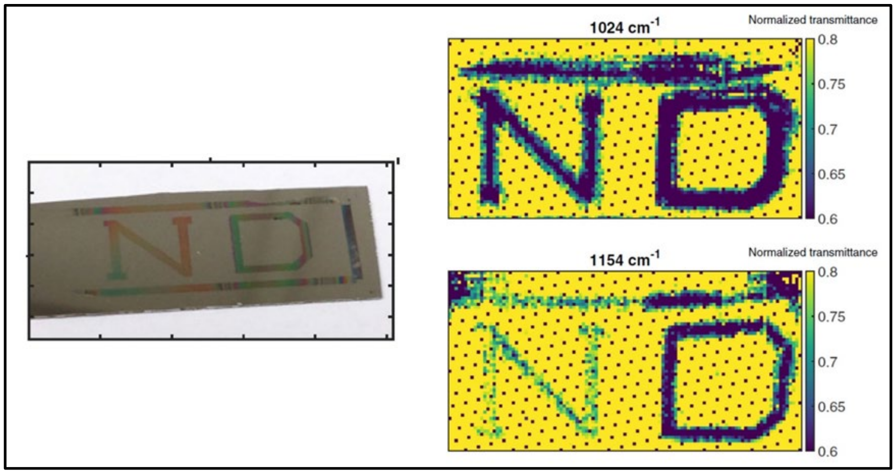

Figure 3: Silicon nitride films in the shape of an "N" (1 µm) and "D" (2 µm) are deposited on a germanium substrate (left). Differential absorption imaging was performed by using the low-cost MIR imaging arrays as detectors in a Fourier-transform infrared (FTIR) spectrometer (right). Results above show subtle difference in relative transmission through the "N" and "D" due to subtle differences in nitride deposition conditions.

B.1. Technical Approach

This project is investigating three complimentary technical advancements: (1) On chip heterogeneous integration of widely disparate wavelength MIR lasers; (2) a low-cost vanadium oxide bolometer for explosive detection (which superseded the original goal of investigating MIR coded aperture imaging technology due to the bolometer array's superior size, weight, power, and cost profile); and (3) development of optical sensor selection algorithms to improve sensitivity and speed of complete sensor systems.

B.2. On Chip Heterogeneous Integration of Widely Disparate Wavelength MIR Lasers

The most commonly used and commercially available semiconductor MIR light source is a QCL [8]. QCLs are made into widely tunable devices that can have large ranges over the entire absorption band of explosives residues using external cavity (EC) feedback. These devices, known as EC-QCLs, select wavelength by rotating the incident angle of light on a diffraction grating. Such a system has been of particular interest recently, to detect trace explosives residues on various targets [1-3]. These systems require moving parts and manual assembly; integration would be preferred for simplicity, lower cost, and to improve mechanical reliability. Arrays of lasers can be fabricated in such a way that the lasing wavelength of adjacent lasers is slightly offset, thus producing a discretely tunable source by selectively turning on and off individual lasers [9]. This is the basis of the technology of Pendar Technologies. These lasers have a lateral offset, and thus can use external free space optics to combine the beams into a single output [10]. External beam combining, while not requiring moving parts, requires free space optics and alignment, which adds complexity and renders the devices susceptible to mechanical instability.

The technical approach we are employing is to combine laser arrays on a single chip and on separate chips into a single module using a novel interchip alignment and optical coupling technique. In this technique, individual laser chips are fabricated with extending copper nodules. The chip with nodules is combined with similar chips to form a quasi-monolithic "quilt," from which the name Optical Quilt Packaging (OQP) is derived (see Figure 4).

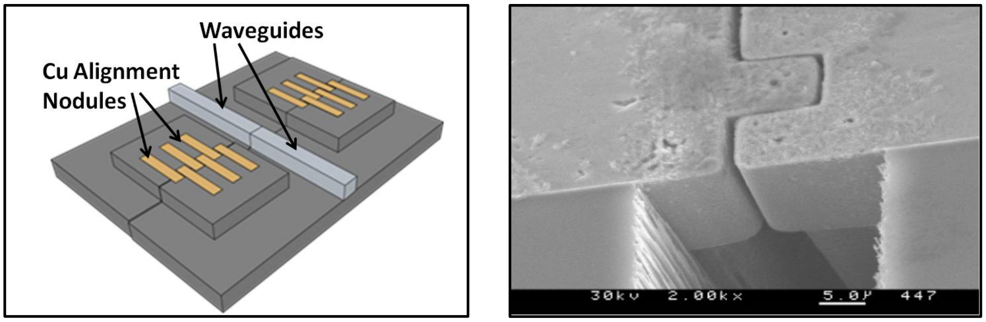

Figure 4: Illustration of OQP (left). SEM micrograph of interlocking quilt packaging nodule structure (right)

The proposed OQP leverages advances in electronic quilt packaging, a novel technique developed at the University of Notre Dame (UND) for high-speed electronic interconnections. Electronic quilt packaging integrates diverse electronic device technologies into a quasi-monolithic module by connecting separate die with solid metallic contacts along the vertical faces for both mechanical and electrical connection. Research at UND has demonstrated the world-record low inter-die insertion loss of less than 0.1 dB from 50 MHz to 100 GHz [11] with submicron alignment.

B.3. MIR Spectroscopic Imaging of Trace Explosives

To increase signal-to-background detection of trace samples of explosives, we will employ MIR spectroscopic imaging. MIR imaging arrays are prohibitively expensive, so we are exploring time and frequency multiplexed imaging with the laser modules developed in this project to improve speed (frame rate) and sensitivity (minimal detectable concentration) of differential reflection spectroscopy by replacing the relatively high-noise infrared detector array with a more sensitive (and less expensive) single element photodetector. MIR trace explosives imaging systems typically employ bolometer (i.e., thermal) or semiconductor detector (i.e., photonic) FPAs. Semiconductor detector arrays exhibit a wavelength dependence on the material; materials useful in the MIR tend to be prohibitively expensive for multipoint distributed sensing. Bolometer-based FPAs can be prohibitively slow for many differential measurement schemes of moving objects; however, recent commercialization of bolometer-based FPAs have drastically reduced system cost by more than 100 fold, opening up new possibilities to investigate using distributed networks of explosive detection systems. To our knowledge, we are the first to explore leveraging these advances and have published the first papers demonstrating hyperspectral chemical imaging using low-cost, microbolometer arrays.

B.4. Improving MIR Spectroscopic Imaging Sensitivity and Specificity

To improve sensitivity and specificity, we are developing a new trace explosive technique based on imaging the thermal relaxation of chemical film residue. MIR explosive residue detection sensitivity and specificity (and therefore accuracy and speed) are limited by the ability to differentiate between the spectral absorption features; however, in real-world environments, substrate and chemical confusants can dramatically reduce performance. Traditionally, this is overcome by imaging samples at many different illumination wavelengths simultaneously; however, such an approach increases system cost and complexity. Our new approach is to not only image the reflected light spectrum but also measure the speed at which thermal energy is dissipated in each point of the image. This added data dimension gives chemical information on the matrix (i.e., binder) of explosive residue and is different for explosives compared to other compounds. We are, to our knowledge, the first to explore this method. It is based on our PI's extensive work on biomedical fluorescence lifetime imaging, which is used to quantitatively measure the chemical microenvironment [12-18].

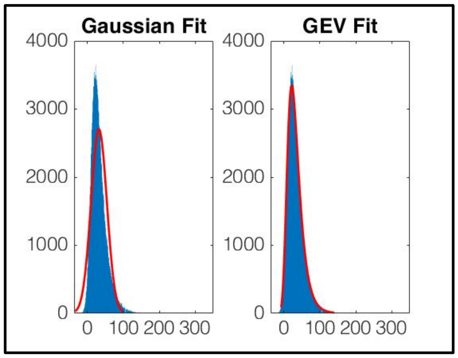

Figure 5: Histograms of pixel values on low SWAP-C MIR imaging platform when field-of-view illuminated by MIR QCL.

Low SWAP-C detectors are typically uncooled microbolometer arrays, and as such, have increased noise compared to the more expensive and power-hungry cooled arrays. To overcome this limitation, co-PI Vijay Gupta is investigating using both Bayesian analytical techniques and machine-learning (dynamic time warping) techniques to increase detection confidence as well as provide a method for efficient sensor selection to maximize confidence using the least number of detection wavelengths. Initial work using Bayesian-based detection has found that noisy microbolometer data actually follows a GEV distribution, not a Gaussian distribution. We believe this to be attributed to the characteristics of bolometer array read-out circuitry, and it yields different analytical models that are commonly used for detection. The GEV distribution is evident in Figure 5 , which shows a pixel intensity histogram of a MIR QCL illuminated scene acquired by a Seek Thermal microbolometer array. Hypothesis testing using GEV yields near unity receiver operator characteristic (ROC) when discriminating hydrocarbons on cardboard; this work is currently being prepared for submission to *IEEE Sensors* and has been extended to explosive residues and dynamic time-warp machine learning in Year 7.

B.5. Distributed and Remote Platform Development

Figure 6: Current wireless sensor nodes for distributed MIR imaging.

The low SWAP-C MIR hyperspectral imaging platform has been enabled by commercially available vanadium oxide microbolometer arrays from several companies (e.g., FLIR and Seek Thermal) that are low-cost (<$250), low-power (<500 mW), small size (2 cm × 2 cm) and low weight (~1 oz). The devices can be controlled over USB and are therefore compatible with a multitude of low-cost single-board computers (SBCs), such as the Raspberry Pi. These traits make them ideal for a low-cost distributed detection platform when combined with a centralized (or ground unmanned vehicle) laser platform or an on-board low-power, pulsed-mode QCL. In Year 7, we integrated our MIR spectroscopic imaging platform inside the radio frequency (RF) EW group in the Sensors and Electron Devices Directorate at the ARL's platform for distributed RF spectrum mapping and sensing. Co-PI Professor Jon Chisum is leading this aspect of the collaboration pursuant to which he has developed the RF sensing component of the platform, and organized field testing with ARL (Figure 6). We have implemented a proof-of-concept demonstration of MIR spectroscopic imaging using these sensor platform nodes by including our custom client-server software written in Python to control and acquire data from MIR microbolometer arrays. We have developed a professional software architecture to enable control and cloud-based data analysis of stand-alone sensing nodes. Additionally, we are leveraging a recent Office of Naval Research (ONR) commitment to fund the translation of the ground-based nodes to unmanned aerial drones. The ONR component is focused on developing on-board RF spectrum mapping and on enhancing communications to support both strong WiFi (i.e., where infrastructure is developed) as well as weak field-based LTE (e.g., in remote areas, forward operating bases, and sea-based platforms). The DHS/ALERT component focuses on (1) the architecture for imaging control and communications, (2) back-end storage and analysis (e.g., real-time on-board "pre-screening" or cloud-based, machine-learning–based analysis), and (3) a graphical user interface for imaging system control and data access.

C. Major Contributions

Year 1: The design and predicted performance of chip-to-chip optical coupling between a QCL ridge waveguide and a single-mode Ge-on-Si waveguide arrays was first published. The system was expected to achieve ~2–6 dB coupling loss within the design tolerance of our system. Our approach is therefore feasible as it would exceed previous state-of-the-art results that demonstrated at best 10 dB couple loss [19-20].

Year 2: Fabrication process was developed and demonstrated for coupling Ge-on-Si waveguide structures via OQP with a chip-to-chip distance. The system used new Ge-on-Si waveguide OQP modules, fabricated and aligned via OQP with interchip distance, and interchip spacing was reduced from 10 µm to 4.6±1.1 µm and lateral misalignment of 920±150 nm. In Year 2, we also optimized our system for peak sensitivity by performing MIR spectroscopic imaging using FTIR. Spectral analysis of the complete explosive (energetic material, binder, and plasticizer) yields the required laser spectra, tuning ranges, power spectral density, and imaging speeds for a required sensitivity and specificity. Trace samples (gloved thumbprints) of C4 (91% RDX) and Semtex-1A (76% PETN, 4.6% RDX) were deposited on bare car-body aluminum, car-body aluminum with car paint and clear coat, and low-reflectivity plastic. Samples were provided by ALERT Thrust leader Professor Steve Beaudoin of Purdue University (Projects R2-A.1, R2-A.3, and R2-D.1). While the HEM components of C4 and Semtex (PETN and RDX) are commonly characterized in the MIR [1] on similar substrates [21], and C4 is well characterized in laboratory settings [4], we sought to establish performance parameters of composite explosives on realistic substrates.

Year 3: OQP fabrication optimization continued, reducing interchip gap of fabricated chips to 1.4±0.3 µm. Insertion loss using MIR OQP was experimentally developed for the measured for the first time to be ~9 dB. We began evaluation of the low-cost vanadium oxide bolometer array that will be used extensively going forward. Chemometric analysis software tools were written for hyperspectral imaging analysis using the new VoX bolometer array that could do PCA analysis imaging on QCL illuminated samples in real time.

Year 4: The project demonstrated a microelectromechanical-systems–based MIR chip-to-chip optical coupling technique, OQP, and demonstrated coupling between two waveguide arrays joined by OQP. The coupling loss between Ge-on-Si passive MIR waveguides is found to be ~4.1 dB, which is the lowest butt-coupling loss ever reported between two chips [22].

Characterization of a low SWAP-C vanadium oxide bolometer array was performed and achieved a 4-times reduction in weight (2.0/0.5 lbs.) and a 48-times reduction cost ($12,000/$250) but takes 93 times longer to achieve the same noise equivalent temperature difference (1.551-second acquisition time for low SWAP-C systems at room temperature compared to 16.6 ms for detector system cooled to 45 mK). Additionally, a proof-of-concept spectral imaging experiment of nitride thin films was demonstrated [7].

Year 5: We developed further hardware modifications and signal processing analysis of the microbolometer imaging platform that lead to an increase in acquisition speed from ~7 frames per second to more than 30 frames per second without negatively affecting the signal-to-noise ratio. We also began our collaboration with Prof. Jon Chisum and the Army Research Lab to integrate our MIR imaging platform in wireless, solar-powered, distributable hardware platforms. Real-time spectroscopic data is streamed to custom control software developed by our group for analysis. This platform subsequently became our primary imaging platform.

Year 6: The project demonstrated a plug-and-play, low SWAP-C, MIR imaging system utilizing a commercially available low-cost vanadium oxide microbolometer controlled via a Raspberry Pi and Python. The camera system was enhanced beyond the reported Year 4 result [7] to achieve 32 frames per second without reducing signal-to-noise ratio. Client-server remote operation was also demonstrated [23].

Year 7: A Bayesian statistical approach was demonstrated to segment polymer films on cardboard using the unique statistical nature of the low SWAP-C vanadium oxide bolometer arrays using MIR spectroscopic imaging. Single-frame analysis could properly identify all 199 images of hydrocarbon films on cardboard [24]. Additionally, convolutional neural networks were applied to the imaging data to increase speed by a factor of 4 for the same signal-to-noise ratio.

D. *Milestones*

- **MIR spectroscopic imaging sensitivity improvements:** To overcome the increased imaging noise that occurs using low SWAP-C–based spectroscopic imaging platforms, we pursued the milestone of using Bayesian statistical techniques to improve detection sensitivity and specificity. We did meet this milestone, however, we did it using machine learning (convolutional neural networks) and not Bayesian statistics. We trained a U-net convolutional neural network, with 12,000 near-infrared images of varying statistical noise properties and demonstrated a 6–9 dB in imaging signal to noise ratio using the low SWAP-C imaging arrays. Image acquisition subsequently increased by a factor of 4 to achieve the same noise level. Denoising is performed in real-time and is compatible with the on-board imaging system in our distributed platform. We originally proposed using cloud computing, but we ended up not needing it to reach this milestone. As part of this milestone, we proposed developing thermal time constant imaging for detection of HEMs as an additional method to increase MIR trace explosive residue imaging sensitivity. Thermal time constants on the order of milliseconds (expected time constant for HEM in binder) are expected to be characterized for the first time and will be a new tool for future HEM detection platform development. While this specific worked was slowed by the University shut down last Spring, we continued developing this approach through extracting 2D thermal diffusivity images of common objects with data collected using our imaging platform in the garage of our technician. Identical materials with different thermal properties were correctly identified using the approach. One-hundred percent of the statistical denoising approach has been achieved in the milestone, and ~50% of the thermal time constant imaging has been achieved.
- **Distributed and remote platform development:** A complete, remote MIR spectroscopic imaging platform has been developed, packaged, and field-tested as a component of the ARL's RF EW group's RF spectrum sensing and mapping platform. During the university shutdown, we in fact used this distributed platform to have different students remotely operating the IR imaging system simultaneously. A signal acquisition and processing pipeline was developed to have multiple "data consumers" (algorithms) analyze data in real time and share the data, remotely, with other "consumers" for further analysis. The system currently consists of ground-based, stand-alone, wireless, mesh network sensor nodes. We have been delayed pursuing aerial drones due to the university shutdown, however, the platform meets the payload specs for aerial drone deployment. Ninety percent of the milestone has been reached (system development, testing, and ground based demonstration). The remaining 10% would be aerial platform demonstration.

E. *Final Results at Project Completion (Year 7)*

- MIR image acquisition, analysis, and distribution was implemented on board the computing and communications hardware for remote aerial vehicles.
- A client, broker, subscriber networking framework was developed and demonstrated for the low SWAP-C MIR imaging systems as part of the Icarus distributed sensing software platform developed by the ARL's EW group. To integrate the system, we improved the systems bandwidth and network latency to allow for streaming of real-time data to a centralized broker. The architecture allows for parallel analysis

and chains of sequence of analysis across multiple cameras using real time data. Distributed analysis of the data (spectroscopic imaging, denoising, and machine-learning classification) was carried out on remote servers as well as on-board systems.

- Hyperspectral imaging of high energetic material films and IED precursors was demonstrated using the low SWAP-C imaging platforms. Detailed noise analysis was conducted to develop new denoising models required to improve low SWAP-C imaging performance.
- Noise analysis of the low SWAP-C imaging platforms found non-Gaussian noise characteristics. Previous detection algorithms assumed Gaussian distribution of pixel intensities. The project demonstrated that using GEV distribution in a Bayesian probabilistic detection model allowed for high sensitivity chemical film detection. This work answers the research question, "does using probabilistic models using GEV distributions improve spectroscopic imaging sensitivity and performance?"
- A new machine-learning technique was developed and evaluated to classify chemical residues by their spectroscopic absorption and thermal time constant (i.e., heating and cooling rates, Figure 7). This enables both chemical integration ("absorption fingerprint") and characterization of the local microenvironment (thermal time constant analysis, e.g., detection of presence of a plastic explosive binder). This work answers the research question, "can inclusion of thermal time constant data improve MIR spectroscopic imaging specificity?"

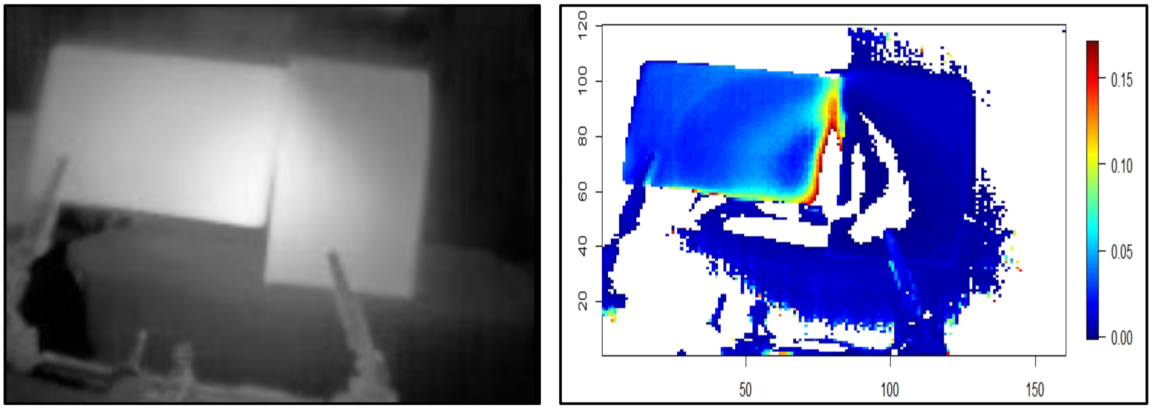

Figure 7: FLIR Lepton image of plastic (left) and glass (right) targets. Demonstration of thermal time constant imaging to segment the materials (right).

- Convolutional neural networks (CNN) were developed and characterized for real-time denoising of MIR images (Figure 8). Since uncooled, low SWAP-C imaging arrays have higher intrinsic noise than the more expensive, larger, high power-consumption counterparts, we employed a new machine-learning–based technique to "restore" the SNR that was sacrificed to achieve low SWAP-C performance. This work answers the research question, "can the increase in imaging noise found in low SWAP-C cameras be improved computationally using machine-learning approaches?"

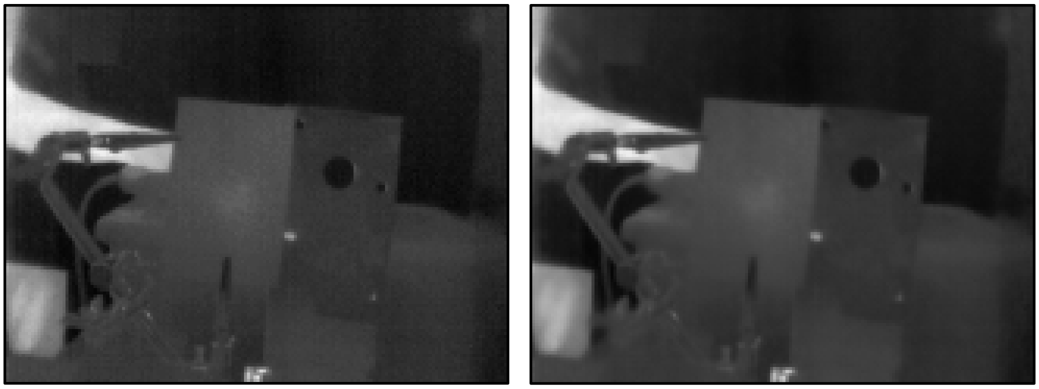

Figure 8: FLIR Lepton raw image (left) and denoised (right) using CNN. Eight-times increase in imaging speed is achieved using machine learning.

- All imaging and analysis were implemented as part of the ARL Icarus distributed sensing software platform and integrated onto the unmanned aerial vehicle computing platforms for the ARL-UND "RadioHound" electromagnetic sensing platform.

III. RELEVANCE AND TRANSITION

A. Relevance of Research to the DHS Enterprise

Remote, standoff detection of explosives residues is a crucial challenge throughout the HSE. While sensitive standoff imaging of residues on the order of 100 $\mu g/cm^2$ and less can be achieved with state-of-the-art equipment, such setups are prohibitively expensive and power hungry. Those limitations severely restrict usage. We address this by developing platforms using off-the-shelf commercial components including low SWAP-C arrays and low-power single-board computers, and we developed machine-learning algorithms and distributed sense/compute models to overcome the limitations of low SWAP-C devices. Our final platform cost 50–100 times less than state-of-the-art approaches and reaches image performance comparable to the more expensive systems. The low SWAP-C platform is also compatible with remote, distributed sensors on weight-sensitive platforms such as for aerial drones.

B. Status of Transition at Project End

The primary end-user application of the project is a distributed MIR spectroscopic imaging platform capable of trace explosive residue imaging. To achieve that end goal, we have demonstrated that low SWAP-C vanadium oxide detectors can perform MIR spectroscopic imaging of trace explosives. We have also developed new machine-learning algorithms to overcome the increased noise in low SWAP-C detector arrays and developed and integrated a new sensor and data analysis architecture on top of the ARL's "Icarus" EW sensing platform. We then demonstrated IR imaging and analysis on remote nodes using the Icarus sensor-control platform.

C. Transition Pathway and Future Opportunities

Transition will be facilitated through the existing collaboration between Co-PI Chisum and the RF EW group at ARL. The sensor-node platform (without MIR imaging capabilities) has been tested as part of the NATO Cyber EW working group field-testing in the UK and Norway in addition to ARL testing performed in the US and is of interest more broadly from within that group. Through Year 7 funding, we have developed an interface for generic sensors (including our IR imaging systems) into their platform and created an analysis "client-subscribe-broker" model to allow for multiple parallel data-analysis workflows on real-time data being acquired by sensors. We have demonstrated MIR imaging capabilities, and machine-learning data analysis, alongside existing RF sensing capabilities on both of the ground-based mesh networks. The results of this work have been committed in real time to the ARL platform.

D. *Customer Connections*

- Jason Kulic (jason.kulick@indianaic.com), Indiana Integrated Circuits, LLC: monthly meetings through Year 5.
- Charles Dietlein, Sensors and Electron Devices, Army Research Laboratory: direct collaborator of Co-PI Chisum. Has already had successful field-testing campaigns for wireless spectrum-sensing platforms, a multi-year ongoing collaboration. Years 6 and 7.
- Kevin Jim, Oceanit, DoD Contractor: collaborator evaluating MIR imaging systems on aerial drones with Navy contract. Completed contract work during Year 6.

IV. PROJECT ACCOMPLISHMENTS AND DOCUMENTATION

A. *Peer Reviewed Journal Articles*

1. Aquino, B., Benirschke, D., Gupta, V., & Howard, S. "A Bayesian Approach to Binary Classification of Mid-Infrared Spectral Data with Noisy Sensors." *IEEE Sensors Journal, 20*(13*),* March 2020, pp. 6964-6970. https://doi.org/10.1109/JSEN.2020.2978757.

B. *Student Theses or Dissertations Produced from This Project*

1. Benirschke, D. "Realization of a Commercially Available, Low-Cost, Spectroscopic, Mid-Infrared Imaging Platform for Enabling Applications and Thermal Time-Harmonic Imaging." PhD, Electrical Engineering, University of Notre Dame, 6 September 2019.

C. *New and Existing Courses Developed and Student Enrollment*

New or Existing	Course/Module/ Degree/Cert.	Title	Description	Student Enrollment
Existing	Course	EE10115: Introduction to Embedded Systems and Internet of Things (SP 2020)	A project-based first-year undergraduate engineering elective course that teaches students the principles of low-power, wireless sensor technology	90

D. *Technology Transfer/Patents*

1. Patents Awarded
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V. REFERENCES

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