REPORT DOCUMENTATION PAGE

Form Approved OMB NO. 0704-0188

The public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggesstions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington VA, 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to any oenalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.
PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ADDRESS.

1. REPORT DATE (DD-MM-YYYY) 18-10-2017	2. REPORT TYPE Final Report	3. DATES COVERED (From - To) 1-Aug-2014 - 31-Jul-2015

4. TITLE AND SUBTITLE
Final Report: A System For Compressive Spectral and Polarization Imaging At Short Wave Infrared (SWIR) Wavelengths

5a. CONTRACT NUMBER
W911NF-14-1-0522

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER
611103

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

6. AUTHORS
Dr. Gonzalo Arce

7. PERFORMING ORGANIZATION NAMES AND ADDRESSES
University of Delaware
210 Hullihen Hall

Newark, DE 19716 -0099

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS (ES)
U.S. Army Research Office
P.O. Box 12211
Research Triangle Park, NC 27709-2211

10. SPONSOR/MONITOR'S ACRONYM(S)
ARO

11. SPONSOR/MONITOR'S REPORT NUMBER(S)
65143-CS-RIP.14

12. DISTRIBUTION AVAILIBILITY STATEMENT
Approved for public release; distribution is unlimited.

13. SUPPLEMENTARY NOTES
The views, opinions and/or findings contained in this report are those of the author(s) and should not contrued as an official Department of the Army position, policy or decision, unless so designated by other documentation.

14. ABSTRACT

The proposed compressive spectral and polarization imaging system at short wave infrared wavelengths has overcome the current limitations of the imaging sensing testbed at the University of Delaware by expanding its sensing capabilities to include sensing in the SWIR region of the EM spectrum. It comprises of three new instruments that when combined with the University of Delaware’s past capabilities allow for the design and optimization of compressive imaging systems, and associated computational imaging algorithms, at wavelengths ranging from the visible to the short-wave IR regions of the EM spectrum.

15. SUBJECT TERMS
Compressive sensing, spectral imaging, polarization, short-wave infrared

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	15. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON Gonzalo Arce
a. REPORT UU	b. ABSTRACT UU	c. THIS PAGE UU	UU		19b. TELEPHONE NUMBER 302-831-1493

RPPR Final Report
as of 25-Oct-2017

Agency Code:

Proposal Number: 65143CSRIP **Agreement Number: W911NF-14-1-0522**

INVESTIGATOR(S):

Name: Gonzalo R Arce
Email: arce@ee.udel.edu
Phone Number: 3028311493
Principal: Y

Name: Javier Garcia-Frias
Email: jgf@udel.edu
Phone Number: 3028310751
Principal: N

Organization: **University of Delaware**
Address: 210 Hullihen Hall, Newark, DE 197160099
Country: USA
DUNS Number: 059007500 EIN: 516000297
Report Date: 31-Oct-2015 Date Received: 18-Oct-2017
Final Report for Period Beginning 01-Aug-2014 and Ending 31-Jul-2015
Title: A System For Compressive Spectral and Polarization Imaging At Short Wave Infrared (SWIR) Wavelengths
Begin Performance Period: 01-Aug-2014 **End Performance Period:** 31-Jul-2015
Report Term: 0-Other
Submitted By: James Kolodzey Email: kolodzey@udel.edu
Phone: (302) 831-2405
Distribution Statement: 1-Approved for public release; distribution is unlimited.

STEM Degrees: **STEM Participants:**

Major Goals: The proposed system will overcome the current limitations of the imaging sensing testbed at the University of Delaware by expanding its sensing capabilities to include sensing in the SWIR region of the EM spectrum. It comprises of three new instruments that when combined with the University of Delaware's current capabilities will allow for the design and optimization of compressive imaging systems, and associated computational imaging algorithms, at wavelengths ranging from the visible to the short-wave IR regions of the EM spectrum.

Accomplishments: The proposed compressive spectral and polarization imaging system at short wave infrared wavelengths has overcome the current limitations of the imaging sensing testbed at the University of Delaware by expanding its sensing capabilities to include sensing in the SWIR region of the EM spectrum. It comprises of three new instruments that when combined with the University of Delaware's past capabilities allow for the design and optimization of compressive imaging systems, and associated computational imaging algorithms, at wavelengths ranging from the visible to the short-wave IR regions of the EM spectrum.

Training Opportunities: Nothing to Report

Results Dissemination: Journals:

C. Fu; M. Don; G. Arce, "Compressive Spectral Imaging via Polar Coded Aperture," in IEEE Transactions on Computational Imaging , vol.PP, no.99, pp.1-1, 2016

H. Rueda, D. Lau and G. R. Arce, “Multi-spectral compressive snapshot imaging using RGB image sensors”, Optics Express, vol. 23, no. 9, pp. 12207-12221, (2015).

C. V. Correa, H. Arguello, and G. R. Arce, "Snapshot colored compressive spectral imager," J. Opt. Soc. Am. A 32, 1754-1763 (2015)

Chen Fu, Henry Arguello, Brian M. Sadler, and Gonzalo R. Arce, "Compressive spectral polarization imaging by a pixelized polarizer and colored patterned detector," J. Opt. Soc. Am. A 32, 2178-2188 (2015)

J. Tan, Y. Ma, H. Rueda, D. Baron and G. R. Arce, “Compressive Hyperspectral Imaging via Approximate Message Passing”, IEEE Journal of Selected Topics in Signal Processing, vol. 10, no. 2, pp. 389-401, (2016).

H. Rueda, H. Arguello and G. R. Arce, “DMD-based implementation of patterned optical filter arrays for compressive spectral imaging”, Journal of the Optical Society of America A, vol. 32, no. 1, pp. 80-89, (2015).

Conference Proceedings:

H. Rueda, H. Arguello, G. R. Arce, “Dual-Arm VIS/NIR Compressive Spectral Imager”, Proceedings of IEEE International Conference on Image Processing (ICIP ’15), Quebec City, Canada, (September 2015).

H. Rueda, H. Arguello, and G. R. Arce, “Colored Coded Aperture Compressive Spectral Imaging: Design and Experimentation”, Proceedings of IEEE Global Conference on Signal and Information Processing (GlobalSIP ’15), Orlando, FL., USA, (December 2015).

H. Rueda, D. Lau, and G. R. Arce, “RGB Detectors on Compressive Snapshot Multi-spectral Imagers”, Proceedings of IEEE Global Conference on Signal and Information Processing (GlobalSIP ’15), Orlando, FL., USA, (December 2015).

C. V. Correa, H. Arguello and G. R. Arce, "Spatio-spectral uniform multi-frame coded apertures for compressive spectral imaging," 2015 IEEE Global Conference on Signal and Information Processing (GlobalSIP), Orlando, FL, 2015, pp. 614-618.

J. Tan, Y. Ma, H. Rueda, D. Baron and G. R. Arce, “Application of Approximate Message Passing in Coded Aperture Snapshot Spectral Imaging”, Proceedings of IEEE Global Conference on Signal and Information Processing (GlobalSIP ’15), Orlando, FL., USA, (December 2015).

L. Galvis, H. Arguello, and G. R. Arce, “Synthetic Coded Apertures in Compressive Spectral Imaging: Experimental Validation”, Proceedings of IEEE Global Conference on Signal and Information Processing (GlobalSIP ’15), Orlando, FL., USA, (December 2015).

Honors and Awards: Nothing to Report

Protocol Activity Status:

Technology Transfer: Nothing to Report

PARTICIPANTS:

Participant Type: Faculty

RPPR Final Report
as of 25-Oct-2017

Participant: Gonzalo Arce
Person Months Worked: **Funding Support:**
Project Contribution:
International Collaboration:
International Travel:
National Academy Member:
Other Collaborators:

Final Report:
A System For Compressive Spectral and Polarization Imaging At Short Wave Infrared (SWIR) Wavelengths

DEFENSE UNIVERSITY RESEARCH INSTRUMENTATION PROPOSAL

1. Summary of the proposed initiative

In this proposal investigators from the Department of Electrical and Computer Engineering (ECE) at the University of Delaware request funds to create a critical capability that will enable the design and optimization of new multi-domain (spectral and polarimetric) compressive imaging systems at short-wave infrared (SWIR) wavelengths --- in the 0.9 to 1.7 um window of the electromagnetic (EM) spectrum. When completed, this imaging system will provide a new experimental capability needed to develop enhanced imaging methods that focus not just on rendering a high fidelity image, but also exploit the wealth of information available within a scene in other attributes, e.g., spectral bands, polarization, sparsity, and radiometric phenomenology, all at SWIR wavelengths. Current capabilities at the University of Delaware are limited to compressive spectral sensing in the visible to near infrared (NIR). Surveillance and targeting in defense applications benefit significantly from SWIR imaging due to the night sky atmospheric phenomena, radiating five to seven times more illumination than starlight, nearly all of it in the SWIR wavelengths. So, with a SWIR imaging system and this night radiance, objects can be seen with great clarity on moonless nights as no other imaging sensor can do.

The proposed system will overcome the current limitations of the imaging sensing testbed at the University of Delaware by expanding its sensing capabilities to include sensing in the SWIR region of the EM spectrum. It comprises of three new instruments that when combined with the University of Delaware’s current capabilities will allow for the design and optimization of compressive imaging systems, and associated computational imaging algorithms, at wavelengths ranging from the visible to the short-wave IR regions of the EM spectrum. Specifically, the proposed system is composed of: (1) an objective lens capable of forming an image of the incoming scene into the image plane of the spatial light modulator, (2) a spatial light modulator and a dispersive element, which respectively codes and shears the focused information in order to have information at specific wavelengths, (3) a set of optical filters which allow to discriminate spectrally the coded and sheared information, and (4) a pixelated polarizer grid attachable to the FPA detector capable of discriminating linear polarization energy at the pixel level. For the correct system execution, (5) a workstation responsible of the spatial light modulator and FPA detector operation, as well as of the sensing and reconstruction procedures is also required. The implementation of this new compressive SWIR imaging system will lead to a wide-band VIS-NIR-SWIR compressive spectral and polarimetric imaging multi-system capable to sense and classify scenes as well as to detect possible anomalies.

2. Actually acquired equipment

The requested equipment comprised a complete *compressive SWIR imaging system* that includes objective lens, spatial light modulator, dispersive element, optical filters, polarization grid and IR spectrometer, along with computer hardware and software for instrumentation control. The price requested for the complete system, including assembly and installation was $89441.30. Although initial equipment was quoted, some of them were modified to match the budget, as well as the entitled research objectives. The following table lists the actually acquired equipment.

Description	Part Name /Number	Vendor	Cost
IR spectrometer	• BTC261P-512-L / Sol 1.7 Spectrometer TE Cooled • BPS2.0 / Fiber coupled 20W Tungsten light source • FRP-200-0.22-1.5-NIR / Fiber optical reflectance probe	BWTEK Inc.	$6,634.30
	• FRPH / Fiber reflectance probe holder • SRR-1.25-99 / White PTFE Reflectance standard	BWTEK Inc.	$549.78
	• B2021 / PoE Bobcat sensor interface	Saber1 Technologies	$5,228.37
	• CoastalOpt UV-VIS-IR 60mm Apo Macro lens	Jenoptik-Inc	$5,817.36
IR light source	• 3900e DC Regulated Light source with Light feedback • 9145 Dual 6” Lightline	Illumination Technologies	$3,299.14
	• EPC660 Light engine evaluation kit	ESPROS Photonics Inc.	$5,000
Objective lens for SWIR	• 50mm F/1.4 SWIR lens (p/n SR1499-A01)	StingRay Optics LLC	$2,115 -$1647.25*

Optical filters and lenses for SWIR	• Optical stuff: Lenses, posts, lens mounts, screws, optical shelf, etc.	Thorlabs Inc.	$5,749.98
	• Infrared optical filters	Edmund Optics	$2,215.99
Dispersive element for SWIR	• SWIR Double-Amici prism	Shanghai Optics Inc.	$3,316.60
Spatial Light Modulator	• PLUTO-NIR-010-A Phase Only LCoS	HOLOEYE Corp.	$15,325.50
	• DLP LightCrafter 4500 / Light engine module	Wintech Digital Systems	$1,322
	• DLP4500NIRFQE / IR chipset for DLP	Digi-key Electronics	$394.57
	• USB-6501, 24-Ch Digital light modulator board	National Instruments	$106.73
Pixelated Polarizer	• LPNIR100-MP2 / IR linear polarized • LTS300, LTSP1, LTSP3 / XYZ Positioning Linear stage • PRM1Z8E / High precision motorized rotation stage	Thorlabs Inc.	$10,240.43
	• Pixelated photomask	Photo sciences Inc.	$2,570.01
	• Precision optical rails	Newport Inc.	$339.88
SWIR Camera	• XEVA-2508	Xenics	$0**
Workstation for compressive optical sensing and reconstruction procedures	• 4.0 GHz Quad-core, Intel Core i7 Computer	Apple Inc.	$4,780
	• Design workstation	Dell Inc.	$1,049.40
	• Portion of cluster node at UD	UD	$1,800
	• LCD display screen mount, Firewire card interface	Amazon	$263.26
	• Kinect sensor and PC interface	Microsoft store and Best buy	$194.98
Additional required stuff	• Optical table	Newport Corp.	$8,572.22
	• Installation optical table	Bruce Industrial Company Inc.	$2,020.28
	• Hard drive and RAM memory	NewEgg Inc	$782.48
	• LED computer display	Staples Direct	$1,399.99
		Total	**$89,441.00**

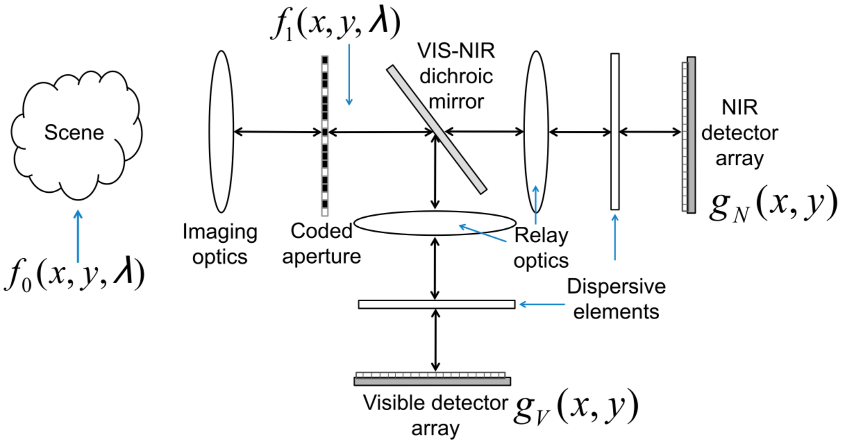
* This was legitimate expense, but purpose was overspent, so some money had to be reallocated to a discretionary account.

**Current capability at UD

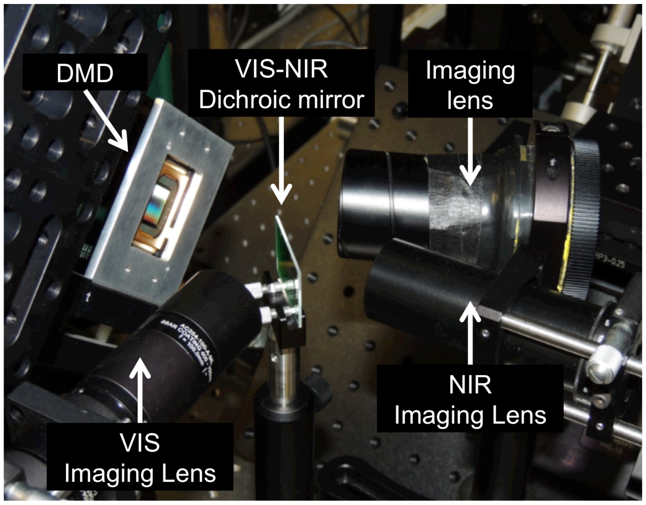
3. Summary of the projects where the acquired equipment is used

3.1 VIS-NIR Dual-arm Compressive Spectral Imager

Due to the rich information contained in both the visible and the NIR spectrum, a dual-arm VIS-NIR compressive spectral imager, presented in Figure 1, has been developed at UD. This architecture covers a wider-band compressive imaging system capable of identify, classify and detect objects in both domains. We mathematically modeled and demonstrated its implementation covering the visible and the near infrared spectra between 448 nm to 1436 nm. Particularly, we developed a Digital-Micromirror-Device-based CSI system, which implements dual-band CS measurement processes of 3D spatio-spectral scenes. The results attained with this architecture has been published in the IEEE International Conference on Image Processing (ICIP), with the paper titled "DUAL-ARM VIS/NIR COMPRESSIVE SPECTRAL IMAGER". Furthermore, a journal paper is currently being developed aiming to be published in an OSA letters journal.



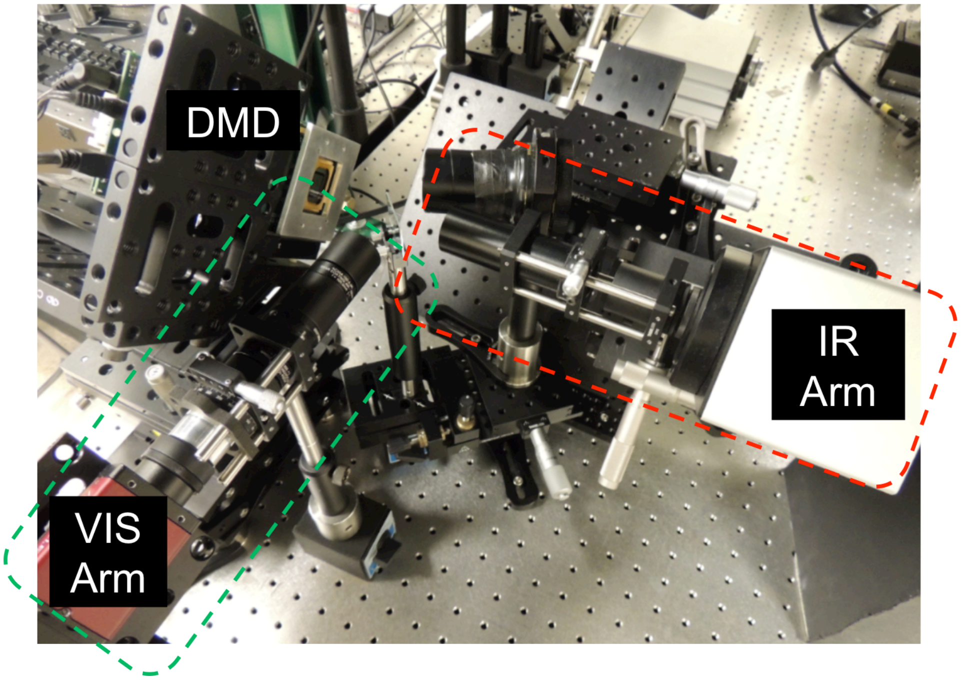
(a) Dual arm optical design



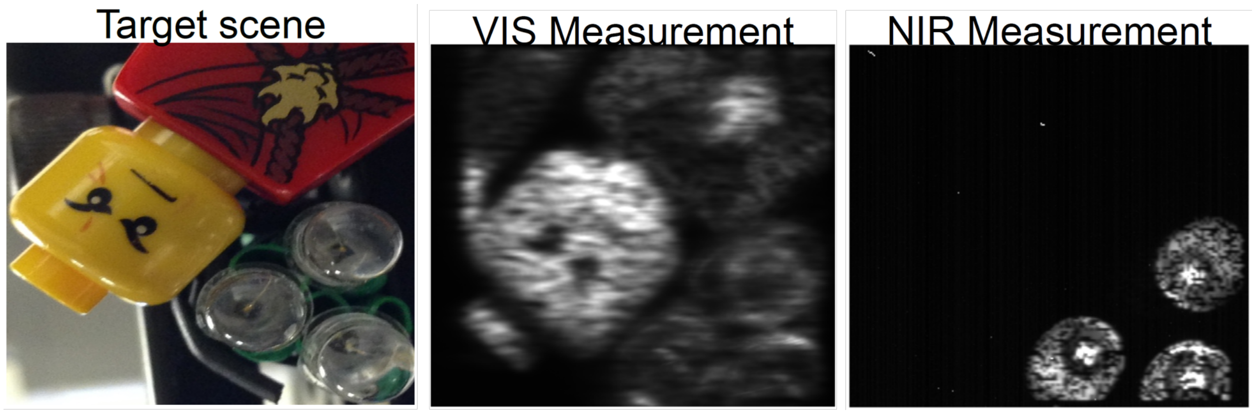
(b) Dual-arm optical elements

Figure 1. VIS-NIR dual-arm compressive architecture. (a) Optical design, (b) Testbed

Figure 2 depicts the actually developed dual-arm testbed along with a set of measurements from the visible and NIR sensors when capturing the target scene composed by a Lego object and 3 LEDs with pick responses at 1050 nm, 1200 nm and 1300 nm, respectively.



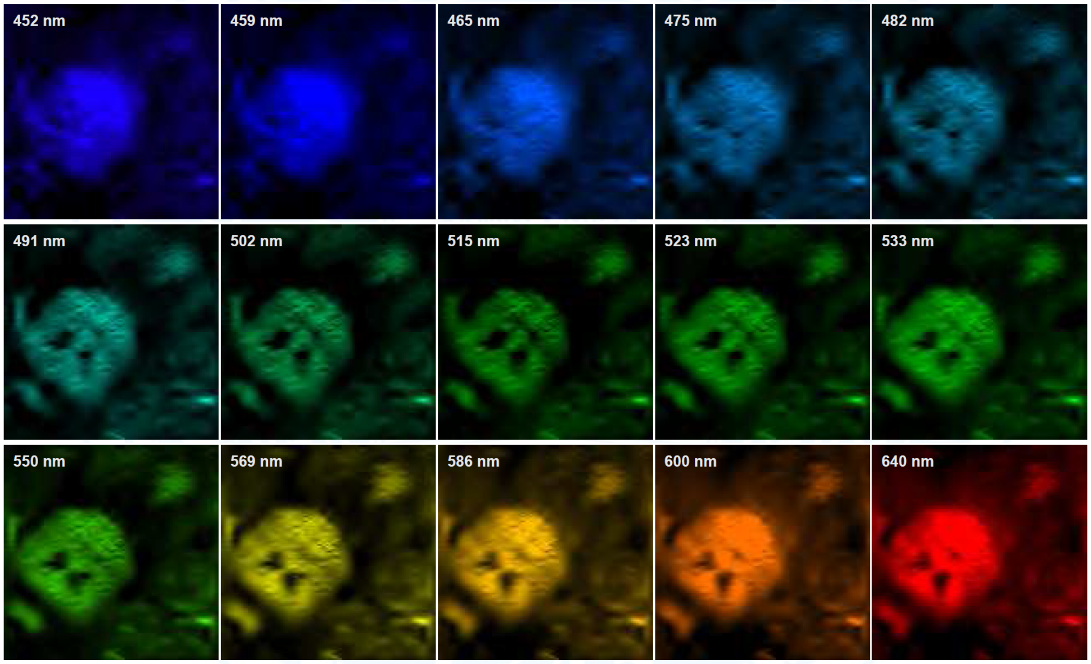
(a) Testbed setup



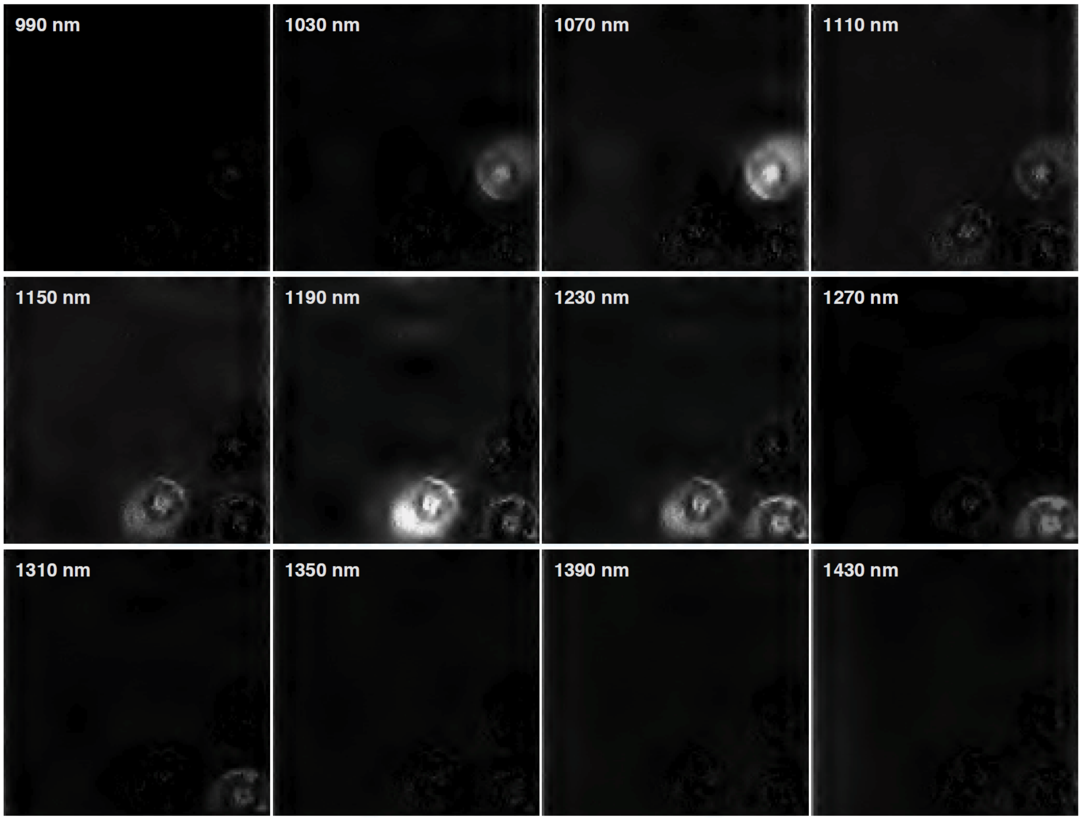
(b) Target scene and compressive measurements

Figure 2. Visible+NIR testbed setup built in our lab, and the attained compressive measurements from the visible and the NIR sensors.

Figure 3 shows the spectral datacube reconstructions attained from the compressive measurements shown in Fig. 2. In particular a calibration data cube was captured per each different coding pattern to estimate the PSF of both imaging arms, by illuminating a completely white target with a visible-to-NIR monochromator spanning the spectral range between 448nm to 1436nm. Based on the calibration data cubes and the compressive measurements, the Gradient Projection for Sparse Reconstruction (GPSR) algorithm was used to recover an estimation of the scene.



(a) Visible datacube reconstruction attains 15 visible spectral bands



(b) NIR datacube reconstruction attains 12 infrared spectral bands

Figure 3. Reconstructed datacubes attained with the dual arm architecture, using 6 snapshots.

3.2 Spectral and Polarimetric Imaging Multi-Domain System

With the granted funds, a SWIR spectral/polarimetric compressive imaging system is currently being developed at UD. This system is a critical piece of a larger system dedicated towards the development of optimal computational imaging algorithms for target identification, target classification, and anomaly detection tasks needed in defense research. Figure 5 shows the advances in the testbed setup being developed. It shows most of the acquired equipment including, the SWIR objective lens, mounted in an optical post; the pixelated photomask (or spatial light modulator) precisely positioned and moved through by the XYZ linear stages; the set of optical filters mounted on a filter wheel which automatically switches the filters; the SWIR linear polarizer mounted on the high-precision motorized rotation stage that change precisely the angle of rotation to model different polarization levels; the relay imaging system which includes a set of SWIR imaging lens and a SWIR double Amici prism, optically designed and custom built for our system; and the SWIR camera sensor, previous capability at UD, which limits the spectrum to lie between 0.9 um and 1.7 um.

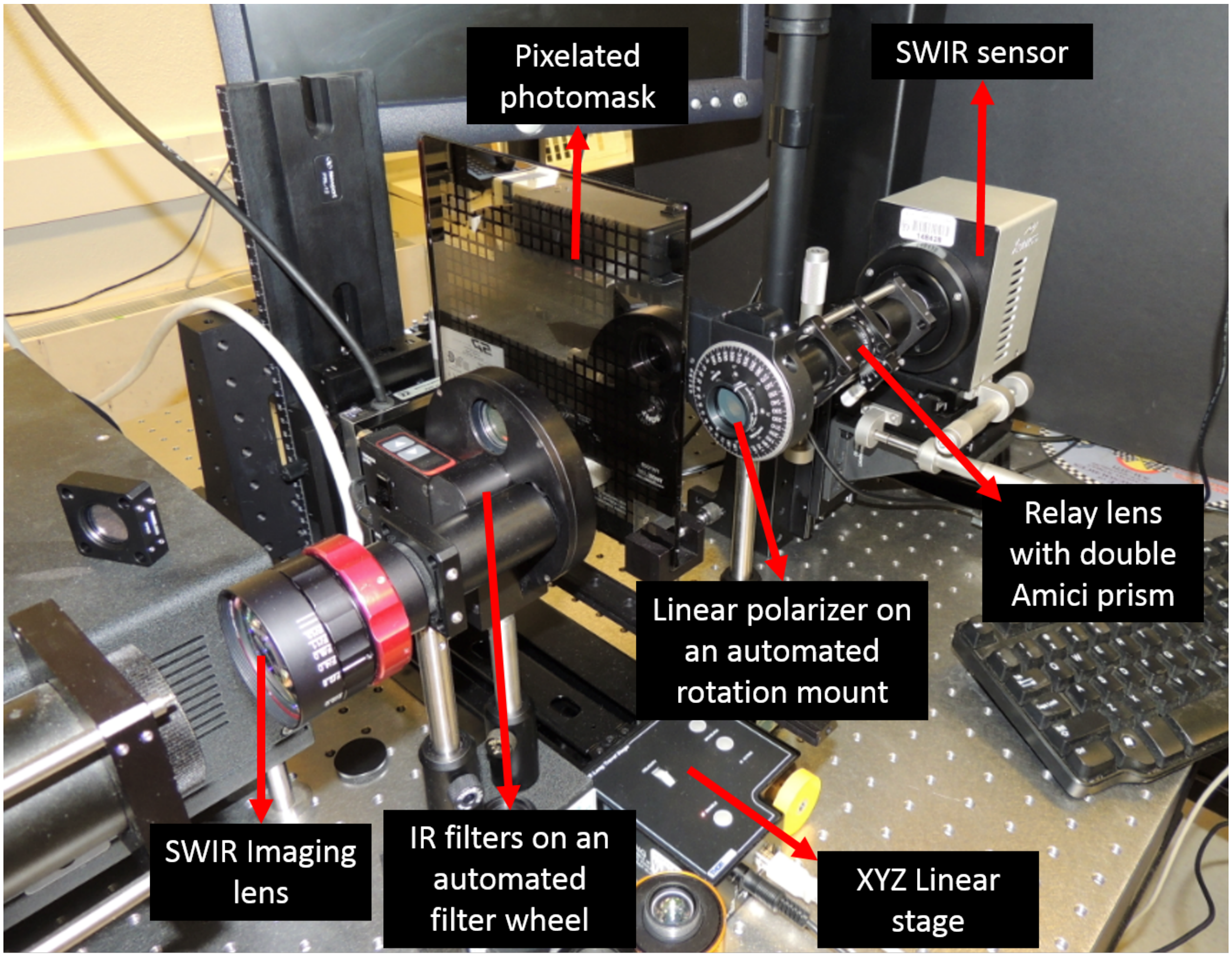


Figure 5. Testbed setup of the spectral and polarimetric imaging SWIR system

In addition, a test and validation setup was mounted next to the spectral and polarimetric testbed, as shown in Figure 6. This test and validation setup includes, the IR spectrometer coupled with the IR tungsten lamp through the optical fiber reflectance probe, mounted on the fiber reflectance probe holder, and the white PTFE reflectance standard, used to measure the reference spectrums. In particular, reflectance measurements are captured from the target scene, and compared against the reconstruction attained with the testbed system.

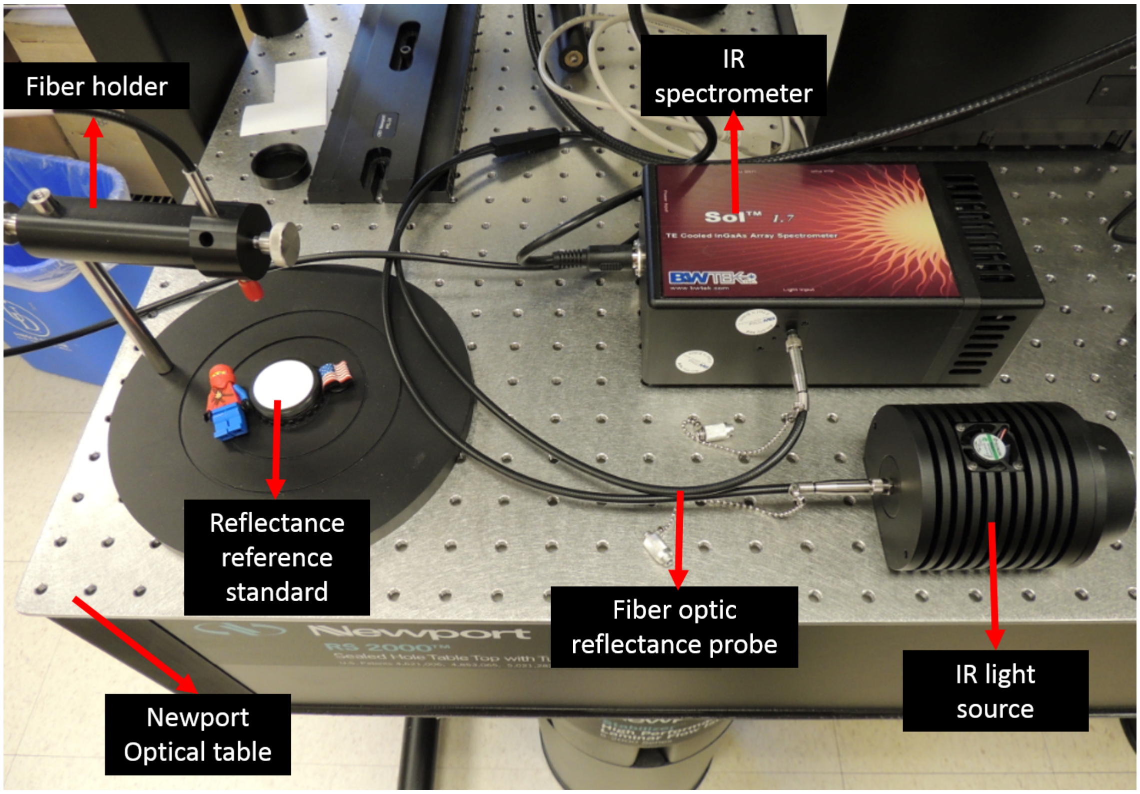


Figure 6. Test and validation setup

Although the complete system has not been finished yet, the main objective is to be capable of conducting computer design, simulation, implementation and experimental spectral characterization of target scenes in the VIS-NIR-SWIR spectrum range. The eventual goal is that the entire spectral range can be sensed in the same time window, leading to a broad source of resources, which can be exploited to have specific information of desirable objects in a specific wavelength range.

4. Impact of the acquired instrumentation on current DoD projects

The acquired instrumentation provides a critical and enabling technology at the University of Delaware. It benefits currently funded DoD projects as well as fuel future DoD related research and new educational initiatives, as follows:

- **“A Compressive Sensing Infrared Camera for Spinning Munitions”, funded by the Army Research Laboratory (ARL), 2014-2017 ($329,500). Principal Investigator Gonzalo Arce.**

  A compressive infrared (IR) imaging sensor architecture is to be designed, modeled, simulated, and tested in the laboratory. The imaging sensor exploits the new theory of compressive sensing where random projections of a scene are acquired without first collecting the pixels/voxels. The sensor has the ability to obtain an image with just a few detector elements. The sensor is designed for rotating munitions and thus multiple measurements are taken consecutively as the scene rotates with respect to the munition’s sensor. A testbed demonstration of the proposed imaging sensor is to be developed.

- **“Spectral Image Classification From Optimal Coded-Aperture Compressive Measurements”, funded by the Army Research Office (ARO), 2011-2015 ($150,000). Principal Investigator Gonzalo Arce.**

  ARO has funded the ongoing research in the emerging theory of compressive sensing (CS). In particular, the development of a supervised classification method of hyperspectral images directly from a small set of compressive measurements, obtained using the coded aperture snapshot spectral imaging (CASSI) system. The CASSI system is different than conventional architectures for hyperspectral imaging, such that spectral imaging information of a 3-dimensional cube is captured with a few 2-dimensional focal plane array measurements containing the coded and spectrally dispersed source field. Supervised classification is then performed directly from the compressive measurements based on finding a discriminative sparse representation of each observation pixel in an over-complete dictionary learned directly from the training samples. An estimated sparse representation is obtained from optimal CASSI measurements by solving a sparsity-constrained optimization problem, and is then used to directly determine the class of the unknown pixel.

- **“Overhead-Performance Tradeoffs in Distributed Wireless Networks”, funded by the Air Force Office of Scientific Research (AFOSR) 2012-2015 ($1,400,000). Principal Investigators: L. Cimini, J. Garcia-Frias**

  Future tactical networks will be complex and dynamic, with severe constraints on energy and bandwidth, operating in environments which themselves are dynamics and unpredictable. In addition, to facilitate access and robustness, control will most likely be distributed and local information will be all that is available. Cooperative communications, in which several simple single-antenna nodes transmit jointly as a virtual antenna array, is an attractive technology for future wireless networks. This is because it can allow them to achieve the dramatic energy and bandwidth efficiency and connectivity improvements brought about by using multiple antennas without requiring the additional size, weight, and power requirements of equipping each node with several antennas.

5. Broader Impact

There is significant interest from the DoD in the development of high fidelity sensing in severely degraded environments, such as fog, clouds, rain, dust, smoke, and sea spray. New computational multi-domain imaging methods are needed that can improve the capabilities to navigate, detect and engage targets and improve situational awareness in a broad range of operational conditions. Computational imaging methods that can control the spatial, temporal, spectral, polarization sensing of the scene have the potential for significant improvement in scene characterization.

Through the use of the equipment acquired with this proposal, we aim to create a comprehensive testbed for multi-domain (spectral, spatial, polarization, temporal) compressive imaging spanning a large portion of the electromagnetic spectrum, from VIS to SWIR wavelengths. This capability does not exist currently within any university environment to the best of our knowledge. For this reason, we will open up our facilities to all researchers who are pursuing research in multi-domain compressive imaging. This will foster collaboration amongst DoD researchers and provide a much needed capability to the research community. In addition, we will leverage the proposed system in undergraduate and graduate courses as a mean of demonstrating different imaging modalities and the advantages of imaging in different regions of the EM spectrum. We currently have classes in imaging and in compressive sensing that will directly benefit from this new capability. These courses are also taught periodically in base at ARL Aberdeen for ARL and CERCED engineers and scientists who will also benefit from the data provided by the new imaging system.