REPORT DOCUMENTATION PAGE

Form Approved OMB NO. 0704-0188

1. REPORT DATE (DD-MM-YYYY)	2. REPORT TYPE	3. DATES COVERED (From - To)
01-12-2017	Final Report	10-Mar-2014 - 9-Mar-2017

4. TITLE AND SUBTITLE
Final Report: Multi-Source Fusion for Explosive Hazard Detection in Forward Looking Sensors

5a. CONTRACT NUMBER
W911NF-14-1-0114

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHORS

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAMES AND ADDRESSES
Mississippi State University
133 Etheredge Hall, 449 Hardy Road

Mississippi State, MS 39762 -9662

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)
65266-CS.18

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

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	15. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			Derek Anderson
UU	UU	UU	UU		19b. TELEPHONE NUMBER 662-325-3530

RPPR Final Report
as of 07-Dec-2017

Agency Code:

Proposal Number: 65266CS **Agreement Number: W911NF-14-1-0114**
INVESTIGATOR(S):

Name: Derek Anderson
Email: anderson@ece.msstate.edu
Phone Number: 6623253530
Principal: Y

Organization: **Mississippi State University**
Address: 133 Etheredge Hall, 449 Hardy Road, Mississippi State, MS 397629662
Country: USA
DUNS Number: 075461814 EIN: 646000819
Report Date: 09-Jun-2017 Date Received: 01-Dec-2017
Final Report for Period Beginning 10-Mar-2014 and Ending 09-Mar-2017
Title: Multi-Source Fusion for Explosive Hazard Detection in Forward Looking Sensors
Begin Performance Period: 10-Mar-2014 **End Performance Period:** 09-Mar-2017
Report Term: 0-Other
Submitted By: Derek Anderson Email: anderson@ece.msstate.edu
Phone: (662) 325-3530

STEM Degrees: 0 **STEM Participants:** 0

Major Goals: This proposal is in response to sections 5.2 and 4.3 in the U.S. Army BAA W911NF-12-R-0012. The aim of this research is to improve the U.S. Army's ability to detect landmines and explosive hazards in different scenarios using multiple forward looking (FL) sensors, namely infrared (IR), forward looking ground penetrating radar (FLGPR) and visual spectrum (aka color). This is a real problem that has direct impact on the mobility of the U.S. Army and on the safety of our troops. Scientific advancements will come in the form of novel signal and image processing, data fusion and discrimination (pattern recognition) algorithms for multi-CPU and graphics processor unit (GPU) hardware to autonomously process data from different sensors on various platforms. This research is supported by the U.S. Army Night Vision and Electronic Sensors Directorate (NVESD) countermine division in terms of sensors, platforms, data collection and discussions regarding project findings if/when appropriate. High-level project goals include:

1. Research new and adapt existing signal and image processing, feature extraction and detection (pattern analysis) algorithms for FL data from different sensors and platforms.
2. Investigate the strengths and weaknesses of various sensors and algorithms in terms of direct detection, context identification and cuing processes in FL sensors.
3. Research fusion at different levels for multiple sensors, features and algorithms.
4. Investigate efficient parallel algorithm implementations for multi-CPU and multi-GPU.
5. Investigate new ways to transfer/adapt a system learned in one environment to another using a limited collection of labeled and/or unlabeled data from the new target environment.
6. Conduct extensive performance tests on various sensors, targets, clutter and environments.

While different tools (mathematics) will be explored, novel research contributions include:

1. Optimization of the structure and aggregation of spectral information across a filter bank to improve explosive hazard detection (EHD) performance and/or efficiency.
2. Research and develop soft features/descriptors to improve the robustness of EHD.
3. Explore measure and integral theory-based multiple kernel (MK) aggregation and its learning (MKL) for non-linear input space fusion of multi-source (sensor) heterogeneous data.
4. Explore MKL-based transfer learning and domain adaptation to improve system performance across environments using limited labeled and/or unlabeled data from the target environment.

The above research is anticipated to lead to a significant improvement in positive detection (PD) and/or false alarm (FA) reduction for EHD. It will also give rise to new mathematics for multisource heterogeneous sensor data fusion,

signal and image processing and pattern recognition.

A significant element of the proposed project is extensive real world experimentation. This is possible in part to a working collaboration with NVESD. The result is continuous performance evaluation of the proposed research for large data sets from various sensor platforms at different U.S. Army test sites. This includes factors such as testing different sensor technologies, different bands, target types, burial conditions, depths, locations and times of day. In addition, since NVESD is helping to field these different sensing technologies and they are helping us carry out experimentation, the majority of funding requested from ARO is dedicated to undergraduate and graduate student education. Mississippi State University, and specifically the PI, has a strong commitment and track record in recruiting women and underrepresented minorities.

Accomplishments: A number of goals were accomplished under this funding. Significant ones include;

(1) Investigating (a) thermal, (b) synthetic aperture acoustics (SAA) and (c) voxel space Radar for buried and side threat attacks.

(2) With respect to thermal sensing, we developed state-of-the-art feature learning algorithms (evolutionary constructed features), machine learning classifiers (multiple kernel learning-based support vector machine classifiers) and fusion (capacity and choquet integrals). Beyond theory, we published articles and delivered reports to NVESD that detailed the performance (capabilities and limitations) of thermal sensors for buried hazard detection.

(3) With respect to SAA, we developed new approaches in the time and frequency domains for analyzing signature of concealed targets (called Fraz). We also developed a method to extract a multi-spectral signature from SAA and deep learning was used on limited training and class imbalance data to recognize threats. Like above, we published and delivered reports to NVESD detailing our findings on different targets, times of day, environments, etc.

(4) With respect to voxel space Radar, we developed a new prescreener that fused anomaly and direct detection evidence. We also developed a deep learning method to automatically extract features and classify these targets. Specifically, we focused on data augmentation and training "tricks" (like how to visualize and ensure that the networks are learning the target concepts). Like above, publications and reports were given with respect to experiments at various US Army test sites.

These are just some of the major goals accomplished under this funding. The publications detail more information and NVESD is in possession of reports that were not released outside of Army. This work resulted in analysis and advancements in

i) sensors
ii) sensor fusion
iii) features and feature learning
iv) advanced classifiers
v) specific machine learning algorithms for SAA, thermal and voxel space radar
vi) reports on sensor and data analysis for domain transfer to Army

In addition, as the works below indicate, other more theory oriented papers resulted form this work (beyond multi-sensor processing and fusion); e.g., "Fuzzy Choquet Integration of Homogeneous Possibility and Probability Distributions".

The PI, university, students and beyond are all grateful for the support from ARO and NVESD.

Last, a number of students were funded and graduated under this work (detailed in another section).

Published works include:

Book chapters and features works:

T.C. Havens, D.T. Anderson, K. Stone and J. Becker, “Computational Intelligence Methods in Forward-Looking Explosive Hazard Detection,” Recent Advancements in Computational Intelligence in Defense and Security,

Springer, 2015

D.T. Anderson, S.R. Price, T.C. Havens, A. Pinar, “Computational intelligence in forward-looking explosive hazard detection”, SPIE newsroom, Dec 23rd, 2015

Journals:

A. Pinar, D. T. Anderson, T. Havens, A. Zare, T. Adeyeba, "Measure of the Shapley Index for Learning Lower Complexity Fuzzy Integrals," Granular Computing, accepted May, 2017

A. Pinar, J. Rice, L. Hu, D. T. Anderson, T. C. Havens, "Efficient Multiple Kernel Classification using Feature and Decision Level Fusion," IEEE Trans. on Fuzzy Systems, accepted September, 2016

D. T. Anderson, P. Elmore, F. Petry, T. Havens, "Fuzzy Choquet Integration of Homogeneous Possibility and Probability Distributions," Information Sciences, accepted April, 2016

Conference:

S. Price, D. T. Anderson, "Genetic Programming-Based Image Feature Learning," CEC, 2017

R. Smith, D. T. Anderson, A. Zare, J. E. Ball, B. Alvey, "Genetic Programming Based Choquet Integral for Multi-Source Fusion," FUZZ-IEEE, 2017

A. Pinar, T. Havens, M. Islam, D. T. Anderson, "Visualization and Learning of the Choquet Integral With Limited Training Data," FUZZ-IEEE 2017

B. Murray, D. T. Anderson, R. Luke, K. Williams, J. E. Ball, "Multispectral signal processing of synthetic aperture acoustics for side attack explosive ballistic detection," SPIE, 2017

J. Dowdy, B. Brockner, D. T. Anderson, K. Williams, R. Luke, "Voxel-space Radar signal processing for side attack explosive ballistic detection," SPIE, 2017

A. Pinar, J. Rice, T. C. Havens, M. Masarik, J. Burns, D. T. Anderson, "Explosive Hazard Detection with Feature and Decision Level Fusion, Multiple Kernel Learning, and Fuzzy Integrals," SSCI, 2016

X. Du, A. Zare, J. M. Keller, D. T. Anderson, "Multiple Instance Choquet Integral for Classifier Fusion," FUZZ-IEEE, 2016

S. R. Price, B. Murray, L. Hu, D. T. Anderson, T. Havens, R. Luke, J. M. Keller, "Multiple kernel based feature and decision level fusion of iECO individuals for explosive hazard detection in FLIR imagery," SPIE Defense, Security, and Sensing, 2016

J. Dowdy, D. T. Anderson, R. Luke, J. E. Ball, T. Havens, J. M. Keller, "Comparison of spatial frequency domain features for the detection of side attack explosive ballistics in synthetic aperture acoustics," SPIE Defense, Security, and Sensing, 2016

A. Pinar, T. Havens, D. T. Anderson, L. Hu, "Feature and decision level fusion using multiple kernel learning and fuzzy integrals," IEEE International Conference on Fuzzy Systems, 2015

D. Shaw, K.C. Ho, J. M. Keller, M. Popescu, D. T. Anderson, R. H. Luke, B. Burns, "Explosive Hazard Detection using MIMO Forward-Looking Ground Penetrating Radar," SPIE Defense, Security, and Sensing, 2015

S. Price, D. T. Anderson, T. Havens, "Fusion of iECO image descriptors for buried explosive hazard detection in forward looking imagery," SPIE Defense, Security, and Sensing, 2015

S. Price, D. T. Anderson, J. M. Keller, "Design of a buried explosive hazard pre-screener in forward looking imagery based on Shearlet filtering and image processing," SPIE Defense, Security, and Sensing, 2015

S. Ravinder, S. Price, D. T. Anderson, "Extended Adaptive Mutation Operator for Training an Explosive Hazard

Detection Prescreener in Forward Looking Infrared Imagery," SPIE Defense, Security, and Sensing, 2015

S. R. Price, D. T. Anderson, R. H. Luke, "An Improved Evolution-COnstructed (iECO) Features Framework," IEEE Symposium Series on Computational Intelligence, 2014

Training Opportunities: Nothing to Report

RPPR Final Report
as of 07-Dec-2017

Results Dissemination: The following is a list of results disseminated to the public (after gov approval!).

In addition, we have biweekly meetings with NVESD. They have presentations from us for the entire reporting period. This also includes yearly meetings that we present our findings at and discuss the future. Robert Luke, Kate Williams and Ken Yasuda at NVESD have copies of all of these reports.

Book chapters and features works:

T.C. Havens, D.T. Anderson, K. Stone and J. Becker, “Computational Intelligence Methods in Forward-Looking Explosive Hazard Detection,” Recent Advancements in Computational Intelligence in Defense and Security, Springer, 2015

D.T. Anderson, S.R. Price, T.C. Havens, A. Pinar, “Computational intelligence in forward-looking explosive hazard detection”, SPIE newsroom, Dec 23rd, 2015

Journals:

A. Pinar, D. T. Anderson, T. Havens, A. Zare, T. Adeyeba, "Measure of the Shapley Index for Learning Lower Complexity Fuzzy Integrals," Granular Computing, accepted May, 2017

A. Pinar, J. Rice, L. Hu, D. T. Anderson, T. C. Havens, "Efficient Multiple Kernel Classification using Feature and Decision Level Fusion," IEEE Trans. on Fuzzy Systems, accepted September, 2016

D. T. Anderson, P. Elmore, F. Petry, T. Havens, "Fuzzy Choquet Integration of Homogeneous Possibility and Probability Distributions," Information Sciences, accepted April, 2016

Conference:

S. Price, D. T. Anderson, "Genetic Programming-Based Image Feature Learning," CEC, 2017

R. Smith, D. T. Anderson, A. Zare, J. E. Ball, B. Alvey, "Genetic Programming Based Choquet Integral for Multi-Source Fusion," FUZZ-IEEE, 2017

A. Pinar, T. Havens, M. Islam, D. T. Anderson, "Visualization and Learning of the Choquet Integral With Limited Training Data," FUZZ-IEEE 2017

B. Murray, D. T. Anderson, R. Luke, K. Williams, J. E. Ball, "Multispectral signal processing of synthetic aperture acoustics for side attack explosive ballistic detection," SPIE, 2017

J. Dowdy, B. Brockner, D. T. Anderson, K. Williams, R. Luke, "Voxel-space Radar signal processing for side attack explosive ballistic detection," SPIE, 2017

A. Pinar, J. Rice, T. C. Havens, M. Masarik, J. Burns, D. T. Anderson, "Explosive Hazard Detection with Feature and Decision Level Fusion, Multiple Kernel Learning, and Fuzzy Integrals," SSCI, 2016

X. Du, A. Zare, J. M. Keller, D. T. Anderson, "Multiple Instance Choquet Integral for Classifier Fusion," FUZZ-IEEE, 2016

S. R. Price, B. Murray, L. Hu, D. T. Anderson, T. Havens, R. Luke, J. M. Keller, "Multiple kernel based feature and decision level fusion of iECO individuals for explosive hazard detection in FLIR imagery," SPIE Defense, Security, and Sensing, 2016

J. Dowdy, D. T. Anderson, R. Luke, J. E. Ball, T. Havens, J. M. Keller, "Comparison of spatial frequency domain features for the detection of side attack explosive ballistics in synthetic aperture acoustics," SPIE Defense, Security, and Sensing, 2016

A. Pinar, T. Havens, D. T. Anderson, L. Hu, "Feature and decision level fusion using multiple kernel learning and fuzzy integrals," IEEE International Conference on Fuzzy Systems, 2015

D. Shaw, K.C. Ho, J. M. Keller, M. Popescu, D. T. Anderson, R. H. Luke, B. Burns, "Explosive Hazard Detection using MIMO Forward-Looking Ground Penetrating Radar," SPIE Defense, Security, and Sensing, 2015

S. Price, D. T. Anderson, T. Havens, "Fusion of iECO image descriptors for buried explosive hazard detection in forward looking imagery," SPIE Defense, Security, and Sensing, 2015

S. Price, D. T. Anderson, J. M. Keller, "Design of a buried explosive hazard pre-screener in forward looking imagery based on Shearlet filtering and image processing," SPIE Defense, Security, and Sensing, 2015

S. Ravinder, S. Price, D. T. Anderson, "Extended Adaptive Mutation Operator for Training an Explosive Hazard Detection Prescreener in Forward Looking Infrared Imagery," SPIE Defense, Security, and Sensing, 2015

S. R. Price, D. T. Anderson, R. H. Luke, "An Improved Evolution-COnstructed (iECO) Features Framework," IEEE Symposium Series on Computational Intelligence, 2014

Honors and Awards: Nothing to Report

Protocol Activity Status:

Technology Transfer: We have biweekly meetings with NVESD. NVESD helps by providing sensors, data, domain experts on sensors, etc. As such, we constantly deliver results and codes to DoD.

PARTICIPANTS:

Participant Type: PD/PI
Participant: Derek Thomas Anderson
Person Months Worked: 12.00 **Funding Support:**
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

Participant Type: Graduate Student (research assistant)
Participant: Ryan Smith
Person Months Worked: 6.00 **Funding Support:**
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

Participant Type: Graduate Student (research assistant)
Participant: Josh Dowdy
Person Months Worked: 12.00 **Funding Support:**
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

Participant Type: Graduate Student (research assistant)
Participant: Blake Brockner
Person Months Worked: 12.00 **Funding Support:**

RPPR Final Report
as of 07-Dec-2017

Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

Participant Type: Graduate Student (research assistant)
Participant: Bryce Murray
Person Months Worked: 6.00 **Funding Support:**
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

CONFERENCE PAPERS:

Publication Type: Conference Paper or Presentation **Publication Status:** 1-Published
Conference Name: SPIE Defense, Security, and Sensing, 2014
Date Received: 01-Dec-2017 Conference Date: 05-May-2014 Date Published: 05-May-2014
Conference Location: Baltimore
Paper Title: Investigation of context, soft spatial and spatial-frequency domain features for buried explosive hazard detection in FL-LWIR
Authors: Stanton Price, Derek Anderson, Kevin Stone, James Keller
Acknowledged Federal Support: **Y**

Publication Type: Conference Paper or Presentation **Publication Status:** 1-Published
Conference Name: 2014 SSCI
Date Received: 01-Dec-2017 Conference Date: 20-Dec-2014 Date Published:
Conference Location: Florida
Paper Title: An Improved Evolution-COnstructed (iECO) Features Framework
Authors: Stanton Price, Derek Anderson, Robert Luke
Acknowledged Federal Support: **Y**

Publication Type: Conference Paper or Presentation **Publication Status:** 1-Published
Conference Name: IEEE International Conference on Fuzzy Systems
Date Received: 01-Dec-2017 Conference Date: 03-Aug-2015 Date Published:
Conference Location: Greece
Paper Title: Feature and decision level fusion using multiple kernel learning and fuzzy integrals
Authors: Anthony Pinar, Tim Havens, Derek Anderson, Lequn Hu
Acknowledged Federal Support: **Y**

Publication Type: Conference Paper or Presentation **Publication Status:** 1-Published
Conference Name: International Geoscience and Remote Sensing Symposium
Date Received: 01-Dec-2017 Conference Date: 27-Jul-2015 Date Published:
Conference Location: Italy
Paper Title: Soft segmentation weighted iECO descriptors for object recognition in satellite imagery
Authors: Stanton Price, Derek Anderson, Matthew England, Grant SCott
Acknowledged Federal Support: **Y**

RPPR Final Report
as of 07-Dec-2017

Publication Type: Conference Paper or Presentation **Publication Status:** 1-Published
Conference Name: SPIE Defense, Security, and Sensing
Date Received: 01-Dec-2017 Conference Date: 20-Apr-2015 Date Published:
Conference Location: Baltimore
Paper Title: Fusion of iECO image descriptors for buried explosive hazard detection in forward looking imagery
Authors: Stanton Price, Derek Anderson, Tim Havens
Acknowledged Federal Support: **Y**

Publication Type: Conference Paper or Presentation **Publication Status:** 1-Published
Conference Name: SPIE Defense, Security, and Sensing
Date Received: 01-Dec-2017 Conference Date: 20-Apr-2015 Date Published:
Conference Location: Baltimore
Paper Title: Design of a buried explosive hazard pre-screener in forward looking imagery based on Shearlet filtering and image processing
Authors: Stanton Price, Derek Anderson, James Keller
Acknowledged Federal Support: **Y**

Publication Type: Conference Paper or Presentation **Publication Status:** 1-Published
Conference Name: SPIE Defense, Security, and Sensing
Date Received: 01-Dec-2017 Conference Date: 20-Apr-2015 Date Published: 20-Apr-2015
Conference Location: Baltimore
Paper Title: Extended Adaptive Mutation Operator for Training an Explosive Hazard Detection Prescreener in Forward Looking Infrared Imagery
Authors: Ravinder Singh, Stanton Price, Derek Anderson
Acknowledged Federal Support: **Y**

Publication Type: Conference Paper or Presentation **Publication Status:** 1-Published
Conference Name: SPIE Defense + Security
Date Received: 25-Aug-2016 Conference Date: 10-May-2016 Date Published: 10-May-2016
Conference Location: Baltimore, Maryland, United States
Paper Title: Multiple kernel based feature and decision level fusion of iECO individuals for explosive hazard detection in FLIR imagery
Authors: Stanton Price, Bryce Murray, Derek T. Anderson, Tim Havens, Robert Luke, James Keller
Acknowledged Federal Support: **Y**

Publication Type: Conference Paper or Presentation **Publication Status:** 1-Published
Conference Name: SPIE Defense + Security
Date Received: 25-Aug-2016 Conference Date: 10-May-2016 Date Published:
Conference Location: Baltimore, Maryland, United States
Paper Title: Comparison of spatial frequency domain features for the detection of side attack explosive ballistics in synthetic aperture acoustics
Authors: Josh Dowdy, Derek T. Anderson, Robert H. Luke, John E. Ball, James M. Keller, Timothy C. Havens
Acknowledged Federal Support: **Y**

Publication Type: Conference Paper or Presentation **Publication Status:** 1-Published
Conference Name: 2017 IEEE Congress on Evolutionary Computation (CEC)
Date Received: 01-Dec-2017 Conference Date: 05-Jun-2017 Date Published: 12-Jul-2017
Conference Location: Donostia, San Sebastián, Spain
Paper Title: Genetic prOgramming for image feature descriptor learning
Authors: Stanton Price, Derek Anderson
Acknowledged Federal Support: **Y**

RPPR Final Report
as of 07-Dec-2017

Publication Type: Conference Paper or Presentation **Publication Status:** 1-Published
Conference Name: 2017 IEEE International Conference on Fuzzy Systems (FUZZ-IEEE)
Date Received: 01-Dec-2017 Conference Date: 09-Jul-2017 Date Published: 20-Jul-2017
Conference Location: Naples, Italy
Paper Title: Genetic programming based Choquet integral for multi-source fusion
Authors: Ryan Smith, Derek Anderson, Alina Zare, John Ball, Brendan Alvey
Acknowledged Federal Support: **Y**

Publication Type: Conference Paper or Presentation **Publication Status:** 1-Published
Conference Name: 2017 IEEE International Conference on Fuzzy Systems (FUZZ-IEEE)
Date Received: 01-Dec-2017 Conference Date: 09-Jul-2017 Date Published:
Conference Location: Naples, Italy
Paper Title: Visualization and learning of the Choquet integral with limited training data
Authors: Anthony Pinar, Timothy Havens, Muhammad Islam, Derek Anderson
Acknowledged Federal Support: **Y**

Publication Type: Conference Paper or Presentation **Publication Status:** 1-Published
Conference Name: SPIE Defense + Security
Date Received: 01-Dec-2017 Conference Date: 01-May-2017 Date Published: 05-May-2014
Conference Location: Anaheim, California, United States
Paper Title: Multispectral signal processing of synthetic aperture acoustics for side attack explosive ballistic detection
Authors: B. Murray, D. T. Anderson, R. Luke, K. Williams, J. E. Ball
Acknowledged Federal Support: **Y**

Publication Type: Conference Paper or Presentation **Publication Status:** 1-Published
Conference Name: SPIE Defense + Security
Date Received: 01-Dec-2017 Conference Date: 01-May-2017 Date Published:
Conference Location: Anaheim, California, United States
Paper Title: Voxel-space radar signal processing for side attack explosive ballistic detection
Authors: J. Dowdy, B. Brockner, D. T. Anderson, K. Williams, R. Luke
Acknowledged Federal Support: **Y**

Nothing to report in the uploaded pdf (see accomplishments)