Southern University and A & M College, Baton Rouge, LA
Dr. Samuel P. Massie Chair of Excellence Program
August 1, 2010 – September 30, 2016
(DE-NA0000724 Modification 0007)

ABSTRACT

The Southern University Massie Chair of Excellence Program conducted research and educational programs in the Detection and Sensing of Environmental and Chemical Substances using Ad-hoc Wireless Sensor Networks. The objectives for the project were:

1) to investigate temperature and chemical detection sensors;
2) to fabricate and characterize these sensors and to determine their responses to broad based stimuli; and
3) to test, and incorporated these sensors in the data fusion and communication systems.

Our investigations for sensors in an AWSN environment were directed toward two types of sensing technologies: 1) a three-dimensional millimeter-sized multisensor chip mainly made up of micro-sensors, a nano-battery, and smart interface(s) such as microprocessors and A/D converters; and 2) water and airborne biological and chemical sensors. Due to the advancement of sensor technology, our research efforts in this area took on a higher level of complexity. We focused on a generalized data fusion scenario; i.e., Angle of Arrival Based Optimal Multiple Unmanned Airborne Vehicle Trajectory Estimation. Research activities in the areas of networking and communication focused on the development of new and or improved approaches to accomplish more effective techniques to enable network discovery, network control and routing, network security, and tasking and querying in ad hoc wireless networks. In addition, since the effectiveness of some of the above techniques were strongly dependent upon the implementation of the physical transmission facility employed; accordingly, a “bottoms up” approach was employed.

Southern University and A & M College, Baton Rouge, LA
Dr. Samuel P. Massie Chair of Excellence Program
Final Report
August 1, 2010 – September 30, 2016
(DE-NA0000724 Modification 0007)

Detection and Sensing of Environmental and Chemical Substances using Ad-hoc Wireless Sensor Networks

Purpose of Project

The Southern University Massie Chair of Excellence Program conducted research and educational programs in the Detection and Sensing of Environmental and Chemical Substances using Ad-hoc Wireless Sensor Networks.

The goals for the program were:

1) to contribute to the innovation of ad-hoc wireless sensor network technologies to enhance our nation's security and defense capability, as well as the quality of life for its citizens; and
2) to train students in the development and use of these technologies to assure the sustainability of these efforts into the future.

The objectives for the project were:

1) to investigate temperature and chemical detection sensors;
2) to fabricate and characterize these sensors and to determine their responses to broad based stimuli; and
3) to test, and incorporated these sensors in the data fusion and communication systems. In addition, we expanded our data fusion capabilities to be geo-location capable to: 1) quickly and accurately locate threats; and 2) estimate and track these threats accurately and timely.

Research Team:

The research team is presented in the table below:

Research Topics	Lead Researcher
1. Sensor Research	Dr. Fred Lacy
2. Data Fusion	Dr. Jiecai Luo
3. Wireless Communication and Networking	Dr. Xj Chen

Sensor Research

Our investigations for sensors in an AWSN environment were directed toward two types of sensing technologies: 1) a three-dimensional millimeter-sized multisensor chip mainly made up of micro-sensors, a nanobattery, and smart interface(s) such as microprocessors and A/D converters; and 2) water and airborne biological and chemical sensors. For the proposed designs, we developed the sensing structures described below.

a. Multisensor Chip

Our sensor research continued work on the multisensor chip, which included portions of the following:

1. the design and fabrication of a PZT (plumbum (lead) zirconate titanate) film pressure sensor consisting of a PZT (0.5 μm) and LSMO (0.1 μm) film heterostructure;
2. the design and fabrication of a PZT film pressure sensor, designed to be used as an acoustic sensor by measuring acoustic emission (AE) wave propagation through PZT films;
3. the design and fabrication of an infrared-based optical micro-sensor. These devices were fabricated using MEMS-based processing methods;
4. the design and fabrication of a temperature sensor, accomplished by using platinum thin films prepared on (5000) SiO_2/Si substrates by DC magnetron sputtering;
5. the design and fabrication of a vibration sensor consisting of an array of mechanical oscillators. This piezoresistive vibration sensor employed silicon cantilevers with their natural frequencies placed adjacently and having lengths of about 600-μm;
6. the design and fabrication of a chemical sensor, accomplished by using nanoparticle seeds of iron, cobalt, nickel, copper, and silver, and processed by vapor deposition on prefabricated micro hotplates followed by annealing at 500°C prior to self-aligned SnO_2 deposition;
7. the design and fabrication of the interfaces for this multi-sensor were addressable, programmable, self-testing, and compatible with a bidirectional digital bus. The important interfaces that we used were: sensor bus; mps; communication interface; microprocessor interface; ADC; MUX; frequency to digital converter; digital register; and address detector;
8. the design and fabrication of a built-in multisensor lithium-ion nanobattery. The anode is a multi-walled carbon nanotube array electrode. The cathode is a Sulfur-Carbon nanocomposite with elemental sulfur incorporated in porous carbon.
9. The design and fabrication of the packaging consisting of the sensors used eutectic bonding, electrostatic bonding, and low temperature glass bonding. For holes and micro-chamber fabrication we used methods like laser drilling and ion beam milling.

b. Water and Airborne Biological and Chemical Sensors

Our new sensor research focused on water and airborne biological and chemical sensors in support of:

1. the development and characterization of sensors that detected toxic chemical gases/vapors;
2. the development and characterization of an immunosensor that employed the principles of amperometry, volatametry, fluorometry, and piezoelectricity for detection of toxins (stimulates of toxins such as Botulinum toxin and Ricin) and

bacteria (heat sterilized bacteria such as *E. coli, Salmonella, Pathogenic Vibrios, and Lysteria*).

Sensor Research-Related Accomplishments

Publications

- 2 book chapters
- 4 journal papers, and
- 3 conference papers / presentations

2 BOOK CHAPTERS

1. Fred Lacy, "Using Theoretical and Computational Models to Understand How Metals Function as Temperature Sensors", In IGI book titled "Handbook of Research on Computational Simulation and Modeling in Engineering, (accepted).
2. Fred Lacy, "Limitations of Thin Film RTDs for Temperature Sensing", In CMOSET book titled "Industrial Sensors: Devices and Applications", edited by K. Iniewski, Boca Raton FL, CRC/Taylor & Francis, p. 195, 2013.

4 JOURNAL PAPERS

1. Fred Lacy, "An Examination and Validation of the Theoretical Resistivity-Temperature Model for Conductors", Int. J. of Electrical Sci. and Eng. 7(4), p. 869, 2013.
2. Fred Lacy, "Developing a Theoretical Relationship between Electrical Resistivity, Temperature, and Film Thickness for Conductors", Nanoscale Research Letters 6:636, 2011.
3. Fred Lacy, "Evaluating the Resistivity-Temperature Relationship for RTDs and other Conductors", IEEE Sensors Journal 11, p. 1208, 2011.
4. Fred Lacy, "Using Nanometer Thin Films as Temperature Sensors (Constraints from Experimental, Mathematical, and Finite-Element Analysis)", IEEE Sensors Journal 9, p.1111, 2009.
5.

3 CONFERENCE PAPERS / PRESENTATIONS

1. Fred Lacy, "Preparation and Assessment of Thin Films for Use as Ammonia Sensors ", Proceedings of the World Congress on Engineering and Computer Science 2013, Vol. II, 2013
2. Justin Boone, Alen Jones, Fred Lacy, "Initial Characterization of Thin Film Temperature Sensing Thermistors", American Canadian Conference for Academic Disciplines, International Journal of Arts and Sciences, 2009.
3. Neeharika Davuluri, Fred Lacy, Pradeep Bhattacharya, "Development of Miniature Li-Ion Battery for Multi-Sensor Chip", Proceedings of the 2009 ASEE Gulf-Southwest Annual Conference, 2009

Academic-Related Accomplishments

Numerous undergraduate students (9) have participated in sensors research and numerous graduate students (12) have participated in this research and have been trained to fabricate and characterize sensors

9 UNDERGRADUATE STUDENTS

1. Justin Boone
2. Alen Jones
3. Shannun Walker
4. Bron Noel
5. Tige Brown
6. Christian Johnson
7. Latasha Henry
8. Frenika Johnson
9. Joseph Boone

12 GRADUATE STUDENTS

1. Nikhil Modi
2. April Page
3. Tarik Singleton
4. Eddie Patrick
5. Adaryll White
6. Veronique Richardson
7. Tariq Scott
8. Thisara Walpita
9. Neeharika Davuluri
10. Vernon Dutch
11. Audis Truxelo
12. Madhusmita Banerjee

Data Fusion

Due to the advancement of sensor technology, our research efforts in this area took on a higher level of complexity. We focused on a generalized data fusion scenario; i.e., Angle of Arrival Based Optimal Multiple Unmanned Airborne Vehicle Trajectory Estimation.

a. Sensor Based Data Fusion

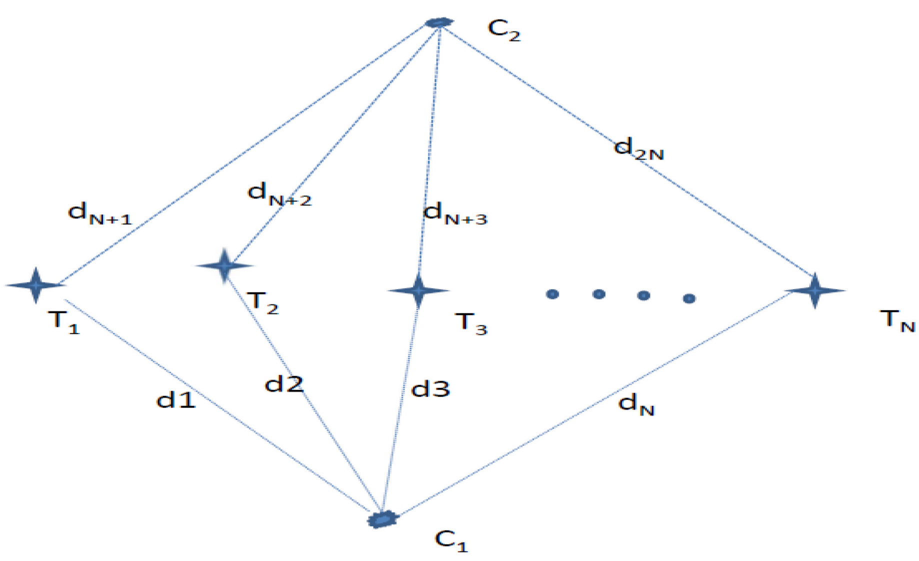
Sensor based data fusion is an emerging technology applied to areas such as automated target recognition, battlefield surveillance, guidance and control of autonomous vehicles, monitoring of chemical and biological agents, complex machinery, medical diagnosis, smart buildings and countless other applications. The specific techniques that were employed in our data fusion investigation are:

1. *Association metrics (AM)* - a general term for assigning a number representing a degree of likeness between data sets. *AM* procedures include: Principal Component Analysis (PCA), a multivariate procedure which rotates data such that maximum variabilities are projected onto axes;
2. *Neural Networks (NN)* - a network of many simple units ("processors"), each possibly having a small amount of local memory; a Fuzzy Logic (FL), a multi-valued logic that allows intermediate values to be defined between conventional evaluations; such as, yes/no, true/false, black/white, etc;
3. *Distributive Processing* - raw sensor signals are sampled and processed and individual relevant summary statistics are extracted from the raw signal, stored locally in individual nodes and may be transmitted to other nodes upon request;
4. *Goal-oriented, On-demand, Processing* - to conserve energy, each sensor node only performs signal processing tasks that are relevant to the current query, or in the absence of a query, retreats into a standby mode; i.e. a sensor does not automatically publish extracted information… it forwards such information only when needed;
5. *Information Fusion* - used to infer global information over a certain space-time region from local observations, Collaborative Signal Processing (CSP) must facilitate efficient, hierarchal information fusion… progressively lower bandwidth information must be shared between node progressively large regions;
6. *Multi-resolution Processing* - depending on the nature of the query, some CSP tasks may require higher spatial resolution involving a finer sampling of sensor nodes, or higher temporal resolution involving higher sampling rates. Space-time processing using wavelets may also be fruitfully exploited in our investigation.

b. Unmanned Airborne Vehicle Based Data Fusion

Given that modern remote sensing systems heavily employ UAVs (unmanned air vehicles) as sensor carriers, it is crucial to control the trajectories of UAVs in order to achieve the best performance in acquiring data. For this purpose, a new approach was used for designing optimal trajectories for UAVs. The optimal UAV trajectory problem to be investigated was as follows: One of our objectives was to estimate the position of target, which can be represented by two coordinates in a reference frame. We considered the problem based on discrete time models. The movement of each UAV can be expressed by a linear difference equation defined in terms of its velocity and positions. By virtue of trigonometry, the AOAs and target distance with respect to a UAV can be expressed in terms of the coordinates of the target and UAV. In practice, the determination of the target position is based on AOAs and target distances observed by all UAVs. As a result of measurement noise, there exists discrepancy between the observed AOAs, target distance and their exact values. For the best estimation of the target position, we divided all UAVs into two groups of approximately equal sizes. If we use a column vector of two elements to represent the position of the target, then we can establish a quasi-linear model such that the observed data is equal to a noise vector plus the products of a coefficient matrix and the position vector. The observed data and the coefficient matrix are functions of observed AOAs, target distances, the positions and velocity of UAVs. To minimize the error for estimating the target position, it is reasonable to introduce a cost function which is a quadratic function of the difference between the observed data and the product of the coefficient matrix and the position vector of the target. Obviously, a smaller value of the cost function meant a more accurate estimation of target position. Since the trajectories of stand-off UAVs were given, the cost function was dependent on the trajectories of moving UAVs (i.e.; UAVs penetrating in the battle field). In other words, the cost function depended on the speed and moving direction of penetrating UAVs. Therefore, the UAV trajectory planning problem was to determine the moving direction and speed of penetrating UAVs to minimize the cost function.

The methods for geo-location based on the Differential time difference of arrival (dTDOA) of the received signals have been in existence for a long time and they have experienced an interesting evolution. The problem based on the AM radio signals is stated as follows to estimate the locations by AM radio signals.



Assume: $T_i = (x_i y_i), i = 1,2,3,\ldots N$ be the known locations of N Transmitters and let $C_1 = (x_{c_1}, y_{c_1})$, $C_2 = (x_{c_2}, y_{c_2})$ be the unknown location of the two receivers. Define

$$
\begin{aligned}
&dT_1T_i = \frac{(d_1 - d_{N+1}) - (d_i - d_{N+i})}{v} \\
&d_1 = \sqrt{(x_{c_1} - x_1)^2 + (y_{c_1} - y_1)^2}, d_{N+1} = \sqrt{(x_{c_2} - x_1)^2 + (y_{c_2} - y_1)^2} \qquad (1) \\
&d_i = \sqrt{(x_{c_1} - x_i)^2 + (y_{c_1} - y_i)^2}, d_{N+i} = \sqrt{(x_{c_2} - x_i)^2 + (y_{c_2} - y_i)^2}, i = 2,3,\ldots N
\end{aligned}
$$

Where dT1Ti *is* a parameter of the differential TDOA between first transmitter and *i-th* transmitter with first receiver and second receiver. Clearly, the equations (1) are nonlinear and must be solved in real time.

The *nuisance variable with* linear equations was used for overcoming the nonlinear equations.

One receiver's location C2 is known:

The equations (1) are modified to

$$
\begin{aligned}
&dT_1T_i = \frac{(d_1 - d_{N+1}) - (d_i - d_{N+i})}{v} \\
&d_1 = \sqrt{(x_{c_1} - x_1)^2 + (y_{c_1} - y_1)^2}, d_{N+1} = \sqrt{(x_{c_2} - x_1)^2 + (y_{c_2} - y_1)^2}\,(given) \\
&d_i = \sqrt{(x_{c_1} - x_i)^2 + (y_{c_1} - y_i)^2}, d_{N+i} = \sqrt{(x_{c_2} - x_i)^2 + (y_{c_2} - y_i)^2}\,(given), \\
&d_i = d_1 + (v \times dT_1T_i + d_{N+i} - d_{N+1}) = d_1 + \Delta d_i, \quad \Delta d_i = v \times dT_1T_i + d_{N+i} - d_{N+1} \\
&i = 2,3,\ldots N \\
&\qquad d_i = \|C_1 - T_i\| = \|C_1 - T_1 + T_1 - T_i\|, \qquad d_i = d_1 + \Delta d_i \\
&\qquad d_1 = \|C_1 - T_1\| \Rightarrow d_i^2 = d_1^2 + 2d_1\Delta d_i + \Delta d_i^2 \\
&\qquad \|C_1 - T_1\|^2 + 2(T_1 - T_i)C_1^T + \|T_1 - T_i\|^2 = d_1^2 + 2d_1\Delta d_i + \Delta d_i^2 \\
&\qquad \Rightarrow (T_1 - T_i)C_1^T = d_1\Delta d_i + \frac{1}{2}(\Delta d_i^2 - \|T_1 - T_i\|^2), i = 2,3,.. \\
&\qquad d_1 = \|C_1 - T_1\|
\end{aligned}
$$

By defining the (N-1)-vectors, h, ρ and the (N-1, 2) matrix G as follows

$$
h = \frac{1}{2}\begin{bmatrix} \|\Delta d_2\|^2 - (\|T_1 - T_2\|)^2 \\ \ldots \\ \|\Delta d_N\|^2 - (\|T_1 - T_N\|)^2 \end{bmatrix}, \rho = \begin{bmatrix} \Delta d_2 \\ \ldots \\ \Delta d_N \end{bmatrix}, G = \begin{bmatrix} T_1 - T_2 \\ \ldots \\ T_1 - T_N \end{bmatrix}
$$

One can easily see that the vector of parameters $C_1 = (x_{c1}, y_{c1})$ is solution of the system of equations ($h \in R^{(N-1)\times 1}, \rho \in R^{(N-1)\times 1}, G \in R^{(N-1)\times 2}$)

$$
\begin{aligned}
&h + \rho d_1 = GC_1^T \\
&d_1 = \|C_1 - T_1\|
\end{aligned} \qquad (2)
$$

Here d_1 is nuisance variable and equation (2) is a linear equation with nuisance variable. It was solved as discussed above.

With the consideration of the measurements always corrupted by noise, then

$$\Delta d_i = v \times dT_1T_i + d_{N+i} - d_{N+1}, \Rightarrow \Delta d_i = \Delta d_i^0 + v \times \Delta t_i, i = 2,3,...N$$
$$dT_1T_i = (dT_1T_i)^0 + \Delta t_i, \Delta d_i^0 = v \times (dT_1T_i)^0 + d_{N+i} - d_{N+1}$$
$$h = \frac{1}{2}\begin{bmatrix} \|\Delta d_2\|^2 - (\|T_1 - T_2\|)^2 \\ ... \\ \|\Delta d_N\|^2 - (\|T_1 - T_N\|)^2 \end{bmatrix} \Rightarrow \approx \frac{1}{2}\begin{bmatrix} \|\Delta d_2^0\|^2 - (\|T_1 - T_2\|)^2 \\ ... \\ \|\Delta d_N^0\|^2 - (\|T_1 - T_N\|)^2 \end{bmatrix} + v\begin{bmatrix} \Delta d_2^0 \Delta t_2 \\ ... \\ \Delta d_N^0 \Delta t_N \end{bmatrix} \Rightarrow$$
$$= h_0 + v \times diag(\Delta d_2^0 ... \Delta d_N^0)\begin{bmatrix} \Delta t_2 \\ ... \\ \Delta t_N \end{bmatrix}$$
$$, \rho = \begin{bmatrix} \Delta d_2 \\ ... \\ \Delta d_N \end{bmatrix} = \begin{bmatrix} \Delta d_2^0 \\ ... \\ \Delta d_N^0 \end{bmatrix} + v\begin{bmatrix} \Delta t_2 \\ ... \\ \Delta t_N \end{bmatrix} = \rho_0 + v\begin{bmatrix} \Delta t_2 \\ ... \\ \Delta t_N \end{bmatrix}$$

$$h_0 + \rho_0 d_1 + v \times diag(\Delta d_2^0 + 1, ... \Delta d_N^0 + 1)\begin{bmatrix} \Delta t_2 \\ ... \\ \Delta t_N \end{bmatrix} = GC_1^T \qquad (3)$$
$$d_1 = \|C_1 - T_1\|$$

Data Fusion Research-Related Accomplishments
5 Conferences/Presentations: IEEE-SSST, SPIE.

1. Jiecai Luo, Ernest Walker, Pradeep Bhattacharya, Xinjia Chen "A New TDOA/FDOA-Based Recursive Geolocation Algorithm," IEEE-SSST, March 7-9 , 2010, Tyler, TX.
2. X. Chen, E. Walker, P. Bhattacharya, and J. Luo, ``Adaptive sphere decoding for space-time codes of wireless MIMO communications," SPIE Conference, Orlando, Florida, 2010.
3. Jiecai Luo, Ernest Walker, Pradeep Bhattacharya, Xinjia Chen " An AOA-based optimal sensor locations' self-adjusting with moving targets' location estimation," SPIE conference paper , April, 2009, Orlando, FL.
4. X. Chen, E. Walker, P. Bhattacharya and J Luo, "Optimization of MIMO Unitary Space-Time Codes," SPIE conference, 2009, Orlando, FL.
5. J. Luo, "An AOA-based optimal sensor deployment for moving target's location estimation," IEEE-SSST, 2008, New Orleans, LA.

Wireless Communications and Networking

Research activities in the areas of networking and communication focused on the development of new and or improved approaches to accomplish more effective techniques to enable network discovery, network control and routing, network security, and tasking and querying in ad hoc wireless networks. In addition, since the effectiveness of some of the above techniques were strongly dependent upon the implementation of the physical transmission facility employed; accordingly, a "bottoms up" approach was employed in the investigation of the following processes defined below.

1. *Physical Channel Processes* - We investigated, using both computational and theoretical techniques, the viability of the Variable Spreading Factor Zero Correlation Zone Code Division Multiple Access (VSF-ZCZ CDMA) sequences, as a method of establishing a secure and agile multiuser wireless channel.
2. *Network Discovery Processes* - We investigated, by both computational and theoretical techniques, network discovery processes, one of which was a multiuser variant of the collision avoidance - carrier sense multiple access (CA-CSMA) access method.
3. *Medium Access Processes* - We investigated, by both computational and theoretical methods, medium access methods for gaining access to the transmission medium for the exchange of data, one of which was a multiuser variant of the token-passing access method.
4. *Higher Level Processes* - Novel processes at the higher levels; i.e.; link and network (packet), was also investigated using both computational and theoretical methods. The primary focus for these processes was to provide an effective transition between the dynamic character for the physical and the medium access processes to a more stable, but responsive, interface to the end-user, via appropriate transport and application processes.

Wireless Research-Related Accomplishments
Publications

- 7 journal papers, and
- 8 conference papers / presentations

7 JOURNAL PAPERS

[1]E. Walker; X. Chen; R. Coope, ``An accurate evaluation of the performance of asynchronous DS-CDMA systems with zero-correlation-zone coding in Rayleigh fading,'' Wireless Sensing, Localization, and Processing, vol. 7706, 2010.

[2] X. Chen and E. Walker, ``Fast detection of network intrusion," Defense Transformation and Net-Centric Systems, vol. 8602, 2011.

3] X. Chen and E. Walker, ``Adaptive sequential methods for detecting network intrusions,'' Sensors, and Command, Control, Communications, and Intelligence, vol. 8711, 2013.

[4] X. Chen and E. Walker, ``Analytic sequential methods for detecting network intrusions,'' Mobile Multimedia/Image Processing, Security, and Applications, vol. 9120, 2014.

[5] X. Chen and E. Walker, ``Adaptive statistical inferential methods for detection and classification in sensor systems,'' Signal Processing, Sensor Fusion, and Target Recognition, vol. 8050, 2011.

[6] J. Chen and X. Chen, ``A new method for adaptive sequential sampling for learning and parameter estimation, Foundations of Intelligent Systems, 2011.
[7] X. Chen, G. Gu and K. Zhou, ``Measurement Complexity of Rayleigh Fading Channels,'' IEEE Transactions on Vehicle Technology, 2009.

8 CONFERENCE PAPERS / PRESENTATIONS

[1] X. Chen and E. Walker, ``A new approach for neural network training and evaluation with applications to sensing systems,'' Proc. SPIE Conferences, Orlando, Florida, June 2011.
[2] X. Chen, P. Bhattacharya, E. Walker and J. Luo , ``An analytic formula for determination of simulation runs for analysis of VLSI circuits,'' Proc. SPIE Conferences, Orlando, Florida, May 2010.
[3] X. Chen and E. Walker, ``Adaptive sphere decoding for space-time codes of wireless MIMO communications,'' Proc. SPIE Conferences, Orlando, Florida, April 2010.
[4] X. Chen and E. Walker, ``New space-time codes for coherent transmission scheme using multiple antennas,'' Proc. SPIE Conferences, Orlando, Florida, June 2012.
[5] X. Chen, E. Walker, P. Bhattacharya, and J. Luo , ``Optimization of MIMO unitary space-time codes,'' Proc. SPIE Conferences, Orlando, Florida, April 2009.
[6] J. Luo, E. Walker, P. Bhattacharya, and X. Chen, ``An AOA-based optimal sensor locations' self-adjusting with moving targets' location estimation,'' Proc. SPIE Conferences, Orlando, Florida, April 2009.
7] X. Chen and E. Walker, ``Noncoherent unitary space-time codes for wireless MIMO communications,'' Proc. SPIE Conferences, Baltimore, Maryland, June 2013.
[8] X. Chen and E. Walker, ``MIMO space-time codes with decoding algorithm of low dimensionality,'' Proc. SPIE Conferences, Baltimore, Maryland, June 2014.

SUMMARY

In summary, the research team was successful to publish in sensor, data fusion, and wireless communication. In addition, they trained undergraduate and graduate students and support summer interns.

Publications

- 2 book chapters
- 12 journal papers, and
- 16 conference papers / presentations

Training

- Trained 9 undergraduate students
- Trained 14 graduate students

Summer Interns Support

- Jillian Crawley-Foster (2011, 2012 and 2014)
- Ronnie Bell (2011 and 2012)
- Antigone Ruth (2011)
- D'Mekeus Cook (2012)
- Derrick Flowers (2013)
- Adrian Anderson (2014, 2015, 2016)
- Paula Mensah (2014, 2015)
- Simone Maiden (2015)
- Drexell Verrette (2016)
- Cameron Johnson (2016)