



---

**System-Theoretic Principles and Decentralized Sensor Network and Control Algorithms for  
Dynamic Data-Driven  
Situational Awareness and Response**

**Tansel Yucelen  
Missouri Univ of Science and Technology Rolla**

---

**08/25/2020  
Final Report**

**DISTRIBUTION A: Distribution approved for public release.**

**Air Force Research Laboratory  
AF Office Of Scientific Research (AFOSR)/ RTA2  
Arlington, Virginia 22203  
Air Force Materiel Command**

DISTRIBUTION A: Distribution approved for public release.

**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 suggestions for reducing the burden, to Department of Defense, Washington Headquarters Services, Directorate for Information Operations and Reports (0704-0188), 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 penalty 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.**

<b>1. REPORT DATE (DD-MM-YYYY)</b> 08/25/2020	<b>2. REPORT TYPE</b> Final Performance Report	<b>3. DATES COVERED (From - To)</b> June 2017-June 2018
--	---	--

<b>4. TITLE AND SUBTITLE</b> System-Theoretic Principles and Decentralized Sensor Network and Control Algorithms for Dynamic Data-Driven Situational Awareness and Response	<b>5a. CONTRACT NUMBER</b> FA9550-17-1-0199
	<b>5b. GRANT NUMBER</b>
	<b>5c. PROGRAM ELEMENT NUMBER</b>

<b>6. AUTHOR(S)</b> Tansel Yucelen	<b>5d. PROJECT NUMBER</b>
	<b>5e. TASK NUMBER</b>
	<b>5f. WORK UNIT NUMBER</b>

<b>7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)</b> Missouri Univ of Science and Technology Rolla Rolla, MO 65409	<b>8. PERFORMING ORGANIZATION REPORT NUMBER</b>
---	---

<b>9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)</b> USAF, AFRL DUNS 143574726 AF OFFICE OF SCIENTIFIC RESEARCH 875 NORTH RANDOLPH STREET, RM 3112 ARLINGTON VA 22203-1954	<b>10. SPONSOR/MONITOR'S ACRONYM(S)</b> AFOSR
	<b>11. SPONSOR/MONITOR'S REPORT NUMBER(S)</b>

**12. DISTRIBUTION/AVAILABILITY STATEMENT**  
Distribution A: Approved for public release

**13. SUPPLEMENTARY NOTES**

**14. ABSTRACT**  
Situational awareness and response technologies using interconnected static and mobile sensors have the capability to enhance combat power and to contribute to the success of non-combat military operations. With this one-year seed funding from April 1, 2017 to March 31, 2018, this project established the fundamental basis of a novel integrated multiagent estimation and control framework for enabling correct, reliable, and communication-efficient dynamic data-driven situational awareness and response applications. Specifically, decentralized information fusion framework was developed for situational awareness in the presence of heterogeneity resulting from the sensing capabilities of nodes and nonidentical sen

**15. SUBJECT TERMS**

<b>16. SECURITY CLASSIFICATION OF:</b>			<b>17. LIMITATION OF ABSTRACT</b>	<b>18. NUMBER OF PAGES</b>	<b>19a. NAME OF RESPONSIBLE PERSON</b>
<b>a. REPORT</b>	<b>b. ABSTRACT</b>	<b>c. THIS PAGE</b>			Tansel Yucelen
U	U	U	UU	7	<b>19b. TELEPHONE NUMBER (Include area code)</b>

## INSTRUCTIONS FOR COMPLETING SF 298

**1. REPORT DATE.** Full publication date, including day, month, if available. Must cite at least the year and be Year 2000 compliant, e.g. 30-06-1998; xx-06-1998; xx-xx-1998.

**2. REPORT TYPE.** State the type of report, such as final, technical, interim, memorandum, master's thesis, progress, quarterly, research, special, group study, etc.

**3. DATE COVERED.** Indicate the time during which the work was performed and the report was written, e.g., Jun 1997 - Jun 1998; 1-10 Jun 1996; May - Nov 1998; Nov 1998.

**4. TITLE.** Enter title and subtitle with volume number and part number, if applicable. On classified documents, enter the title classification in parentheses.

**5a. CONTRACT NUMBER.** Enter all contract numbers as they appear in the report, e.g. F33315-86-C-5169.

**5b. GRANT NUMBER.** Enter all grant numbers as they appear in the report. e.g. AFOSR-82-1234.

**5c. PROGRAM ELEMENT NUMBER.** Enter all program element numbers as they appear in the report, e.g. 61101A.

**5e. TASK NUMBER.** Enter all task numbers as they appear in the report, e.g. 05; RF0330201; T4112.

**5f. WORK UNIT NUMBER.** Enter all work unit numbers as they appear in the report, e.g. 001; AFAPL30480105.

**6. AUTHOR(S).** Enter name(s) of person(s) responsible for writing the report, performing the research, or credited with the content of the report. The form of entry is the last name, first name, middle initial, and additional qualifiers separated by commas, e.g. Smith, Richard, J, Jr.

**7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES).** Self-explanatory.

**8. PERFORMING ORGANIZATION REPORT NUMBER.** Enter all unique alphanumeric report numbers assigned by the performing organization, e.g. BRL-1234; AFWL-TR-85-4017-Vol-21-PT-2.

**9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES).** Enter the name and address of the organization(s) financially responsible for and monitoring the work.

**10. SPONSOR/MONITOR'S ACRONYM(S).** Enter, if available, e.g. BRL, ARDEC, NADC.

**11. SPONSOR/MONITOR'S REPORT NUMBER(S).** Enter report number as assigned by the sponsoring/monitoring agency, if available, e.g. BRL-TR-829; -215.

**12. DISTRIBUTION/AVAILABILITY STATEMENT.** Use agency-mandated availability statements to indicate the public availability or distribution limitations of the report. If additional limitations/ restrictions or special markings are indicated, follow agency authorization procedures, e.g. RD/FRD, PROPIN, ITAR, etc. Include copyright information.

**13. SUPPLEMENTARY NOTES.** Enter information not included elsewhere such as: prepared in cooperation with; translation of; report supersedes; old edition number, etc.

**14. ABSTRACT.** A brief (approximately 200 words) factual summary of the most significant information.

**15. SUBJECT TERMS.** Key words or phrases identifying major concepts in the report.

**16. SECURITY CLASSIFICATION.** Enter security classification in accordance with security classification regulations, e.g. U, C, S, etc. If this form contains classified information, stamp classification level on the top and bottom of this page.

**17. LIMITATION OF ABSTRACT.** This block must be completed to assign a distribution limitation to the abstract. Enter UU (Unclassified Unlimited) or SAR (Same as Report). An entry in this block is necessary if the abstract is to be limited.

---

# SYSTEM-THEORETIC PRINCIPLES AND DECENTRALIZED SENSOR NETWORK AND CONTROL ALGORITHMS FOR DYNAMIC DATA-DRIVEN SITUATIONAL AWARENESS AND RESPONSE

---

## Final Report

FA966017-1-0303 and FA550-17-1-0199\*  
07/15/2017 – 07/14/2018

by

### Tansel Yucelen

Principal Investigator  
Department of Mechanical Engineering  
University of South Florida, Tampa, Florida

### Jagannathan Sarangapani

Co-Principal Investigator  
Department of Electrical and Computer Engineering  
Missouri University of Science and Technology, Rolla, Missouri

for

### Air Force Office of Scientific Research

Dynamic Data-Driven Applications Systems Program

## ABSTRACT

Situational awareness and response technologies using interconnected static and mobile sensors have the capability to enhance combat power and to contribute to the success of non-combat military operations. With this one-year seed funding from April 1, 2017 to March 31, 2018, this project established the fundamental basis of a novel integrated multiagent estimation and control framework for enabling correct, reliable, and communication-efficient dynamic data-driven situational awareness and response applications. Specifically, decentralized information fusion framework was developed for situational awareness in the presence of heterogeneity resulting from the sensing capabilities of nodes and nonidentical sensor types with complementary properties distributed over the network. The decentralized information fusion framework was also integrated with multiagent navigation approach. The goal of this report is to summarize the most important results over the duration of this funding. **A no cost extension until December 2018 was requested but no information was received.**

\* The initial grant was given to the PI, but Tansel moved to a new university. The co-PI remained at the original university and a new grant was spawned, but no new money added. Hence the report covers the performance of both grant numbers at partial amounts.

## 1. INTRODUCTION

The Department of Defense has identified intelligent situational awareness and response technologies as a major research thrust area to enhance combat power and to contribute to the success of noncombat military operations. As advances in VLSI and MEMS technologies have boosted the development of microsensor integrated systems that combine computing and communication on a single platform, future DoD missions will have the capability to exploit large numbers of interconnected low-cost and small-in-size, static and mobile sensors of heterogeneous types with complementary properties. Such large-scale sensor networks will support tasks ranging from environment monitoring and military surveillance, to navigation and control of autonomous ground, underwater, and aerial vehicles.

Motivated from this standpoint, we established system-theoretic principles and decentralized sensor network and control algorithms to enable correct, reliable, and communication-efficient dynamic data-driven situational awareness and response applications. Specifically, decentralized information fusion framework was developed for situational awareness in the presence of heterogeneity resulting from the sensing capabilities of nodes and nonidentical sensor types with complementary properties distributed over the network. The decentralized information fusion framework was also integrated with multiagent navigation approach.

These contributions were reported in the following archival conference and journal papers:

- [1] D. Tran, T. Yucelen, and S. Jagannathan, "On local design and execution of a distributed input and state estimation architecture for heterogeneous sensor networks," American Control Conference, Seattle, WA. (2017)
- [2] D. Tran, T. Yucelen, B. Sarsilmaz†, and J. Sarangapani, "Distributed input and state estimation using local information in heterogeneous sensor networks," *Frontiers in Robotics and AI: Multi-Robot Systems*, Vol. 4, pp. 1-19. (2017)
- [3] D. Tran, T. Yucelen, and J. Sarangapani, "A new result on distributed input and state estimation for heterogeneous sensor networks," ASME Dynamic Systems and Control Conference, Tysons Corner, VA. (2017)
- [4] D. Tran, T. Yucelen, J. Sarangapani, and D. W. Casbeer, "Distributed coestimation in heterogeneous sensor networks with time-varying active and passive node roles," American Control Conference, Milwaukee, WI. (2018)
- [5] D. Tran, T. Yucelen, J. Sarangapani, and D. Casbeer, "Distributed coestimation in heterogeneous sensor networks," *International Journal of Control*. (2019)
- [6] A. Albattat, T. Yucelen, and J. Sarangapani, "An observer-free output feedback co-operative control architecture for linear multiagent systems with event-triggering," American Control Conference, Milwaukee, WI. (2018)
- [7] D. Tran, T. Yucelen, and J. Sarangapani, "Dynamic information fusion with the integration of local observers, value of information, and active-passive consensus filters," AIAA Guidance, Navigation, and Control Conference, San Diego, CA. (2019)

- [8] A. Raj, J. Sarangapani, and T. Yucelen “Event-triggered adaptive distributed state estimation by using active-passive sensor networks,” American Control Conference, Philadelphia, PA. (2019)
- [9] A. Raj, J. Sarangapani, and T. Yucelen, “Distributed state estimation by using active- passive sensor networks,” American Control Conference, Philadelphia, PA. (2019).
- [10] A. Raj, J. Sarangapani, and T. Yucelen, “Distributed state estimation and tracking by using active- passive sensor networks,” International Journal of Adaptive Control and Signal Processing, accepted for publication, December (2019).
- [11] A. Raj, J. Sarangapani, and T. Yucelen, “Distributed adaptive state estimation and tracking scheme for nonlinear systems using active passive sensor networks,” American Control Conference, Denver, CO. (2020)

## **2. DESCRIPTION OF WORK ACCOMPLISHED**

The goal of this section is to summarize the most important results over the duration of this funding.

### **Distributed Input and State Estimation Using Local Information in Heterogeneous Sensor Networks [1,2]**

A new distributed input and state estimation architecture is introduced and analyzed for heterogeneous sensor networks. Specifically, nodes of a given sensor network are allowed to have heterogeneous information roles in the sense that a subset of nodes can be active (that is, subject to observations of a process of interest) and the rest can be passive (that is, subject to no observation). Both fixed and varying active and passive roles of sensor nodes in the network are investigated. In addition, these nodes are allowed to have non-identical sensor modalities under the common underlying assumption that they have complimentary properties distributed over the sensor network to achieve collective observability.

The key feature of our framework is that it utilizes local information not only during the execution of the proposed distributed input and state estimation architecture but also in its design in that global uniform ultimate boundedness of error dynamics is guaranteed once each node satisfies given local stability conditions independent from the graph topology and neighboring information of these nodes. As a special case (e.g., when all nodes are active and a positive real condition is satisfied), the asymptotic stability can be achieved with our algorithm.

### **Distributed Coestimation in Heterogeneous Sensor Networks [3-5]**

The contribution is a new system-theoretical dynamic information fusion framework for heterogeneous sensor networks, where a sensor network with both nonidentical node information roles and nonidentical node modalities is considered. Specifically, nonidentical node information roles allow nodes to be either active or passive in the sense that active nodes receive observations from a process of interest whereas passive nodes do not receive any information. In addition, active and passive roles of nodes can be fixed or varying with respect to time. Furthermore, nonidentical node modalities allow active nodes to receive different classes of measurements from the process.

For this class of sensor networks, we develop a distributed input and state coestimation architecture, where the time evolution of input and state updates of each node both depend on the local input and state information exchanges. Using tools and methods from Lyapunov theory and linear matrix inequalities, we establish stability and performance guarantees of the overall heterogeneous sensor network executing the proposed distributed coestimation architecture under local sufficient conditions for each node. We also consider stochastic extensions that capture the practical aspect when the process and the node observations both include noise.

### **An Observer-Free Output Feedback Cooperative Control Architecture for Linear Multiagent Systems with Event-Triggering [6]**

An event-triggering methodology is proposed on an observer-free output feedback cooperative control scheme for linear multiagent systems in order to schedule the exchanged information between the agents depending upon error exceeding user-defined thresholds for reducing wireless network utilization. Specifically, the cooperative control scheme is designed for continuous-time, minimum phase, and high-order linear multiagent systems in the context of a containment problem (i.e., outputs of the follower agents convergence to the convex hull spanned by those of the leader agents). The proposed observer-free output feedback cooperative control scheme with event-triggering guarantees follower agents' system stability and performance, and also does not yield to a Zeno behavior.

### **Dynamic Information Fusion with the Integration of Local Observers, Value of Information, and Active-Passive Consensus Filters [7]**

We develop a dynamic information fusion framework for sensor networks with the integration of local observers, value of information, and active-passive consensus filters as well as a layer to monitor the validity of information. Specifically, we consider a process of interest consisting of multiple subprocesses (for example, multiple targets to be monitored). The heterogeneity in the sensor networks is considered and handled in many aspects such as nodes are allowed to have different sensing capabilities, different information node roles (active and/or passive; that is, a node can be subject to observations of the process or to no observation), and different weights on information (value of information). In addition, the information validity monitor layer allows operators to evaluate the reliability of the fused information based on the local feedbacks received from the sensor network.

### **Event-Triggered Adaptive Distributed State Estimation by Using Active-Passive Sensor Networks [8]**

A novel event-triggered adaptive observer is developed for each node in the heterogeneous sensor networks (HSNs) in order to estimate state vector of an unknown target or process by using the sensed output when the input to the target/ process is unknown. A subset of nodes in the HSN referred to as active nodes, can sense the target periodically, estimate the target state vector by using their adaptive observer and can communicate the estimated state vector of the target with the neighboring nodes including passive nodes only at event triggered instants. The adaptive observer parameters of active nodes are updated in a periodic fashion. A connected graph defines the local information exchange within the HSN. By using the criterion of collective observability, a novel distributed event-triggered adaptive estimation scheme is introduced where the nodes are allowed

to have different sensor modalities. Using the Lyapunov analysis, uniform ultimate boundedness of the state estimation and the parameter estimation errors are demonstrated.

### **Distributed State Estimation and Tracking by Using Active-Passive Sensor Networks [9,10]**

We develop proposes a novel adaptive observer for heterogeneous sensor networks (HSNs) to estimate state vector of an unknown target or process by using the sensed output when the input to the target/process is also not known. In an HSN, nodes are considered either active or passive depending upon their ability to sense the target output. The local information exchange among the nodes is dictated by a connected graph. By using the criterion of collective observability, a novel distributed adaptive estimation is introduced where the nodes are allowed to have different sensor modalities. Stability analysis shows uniform ultimate boundedness of the state estimation and parameter estimation errors. A tracking scheme is established using the estimated state information and overall convergence is demonstrated.

### **Distributed Adaptive State Estimation and Tracking Scheme for Nonlinear Systems Using Active-Passive Sensor Networks [11]**

We propose a novel adaptive neural network (NN) based distributed state estimation scheme for a heterogeneous sensor network (HSN), to estimate the state vector of an unknown nonlinear process/target by using sensed output when the target input remains unknown. The active nodes in the HSN can sense the target output based on the detection range. By using a connected graph, the active nodes will communicate their estimated state vector from their adaptive NN observer to other passive nodes in the neighborhood that cannot sense the target so as to estimate the target state vector. Next, a subset of nodes in the HSN, referred to as mobile nodes, track the moving target by using their estimated state information and a state feedback controller. For the communication topology considered, it is shown that the distributed state estimation, the NN observer weight estimation, and the tracking errors are uniformly ultimately bounded.

## **3. RESEARCH PERSONNEL SUPPORTED**

### **Faculty**

Tansel Yucelen, Principal Investigator  
Jagannathan Sarangapani, Co-Principal Investigator

### **Graduate Students**

Dzung Tran  
Akhilesh Raj

## **4. INTERACTIONS AND TRANSITIONS**

The following conferences were attended:

American Control Conference 2017  
ASME Dynamic Systems and Control Conference 2017  
American Control Conference 2018

AIAA Guidance, Navigation, and Control Conference 2019  
American Control Conference 2019

In addition, we are planning to attend to the following conference:

American Control Conference 2020

With this one-year seed funding from April 1, 2017 to March 31, 2018, our goal was to establish the fundamental basis of a novel integrated multiagent estimation and control framework for enabling correct, reliable, and communication-efficient dynamic data-driven situational awareness and response applications. We accomplished this through the results summarized in Section 2. In addition, we have disclosed the following invention:

Local Design and Execution of a Distributed Input and State Estimation Method for Heterogeneous Sensor Networks (D. Tran and T. Yucelen), Disclosure No: 17A051