LISC
LABORATORY FOR INTELLIGENT SYSTEMS AND CONTROLS

Information-driven Sensor Path Planning for Mobile Monitoring of Source Emissions

IGERT: Wireless Intelligent Sensor Networks (WISeNet)

Silvia Ferrari
Paul Ruffin Scarborough Associate Professor of Engineering
Duke University

NSF 2012 IGERT Annual Meeting
Technical Science Session on Computation, Sensing, and Devices
Capital Hilton, Washington DC

May 30 - June 1, 2012

1

LISC
LABORATORY FOR INTELLIGENT SYSTEMS AND CONTROLS

Introduction

Modern Sensor Systems – multiple sensors installed on mobile platforms

-- Environmental monitoring and prediction

-- Landmine detection and identification

-- Monitoring of urban environments (disaster relief, security, ..)

Traditional paradigm: sensor information is used as feedback to the vehicle in order to support the vehicle navigation

New paradigm: the sensor motion is planned in view of the expected measurement process, in order to support the sensing objectives

IGERT WISeNet Research Area: Geometric Sensor Path Planning

-- Address couplings between sensor measurements and sensor dynamics
-- Plan sensor motion to optimize sensing objectives
(e.g., sensor coverage, detection, classification, tracking..)

2

LISC
LABORATORY FOR INTELLIGENT SYSTEMS AND CONTROLS

Sensor Model

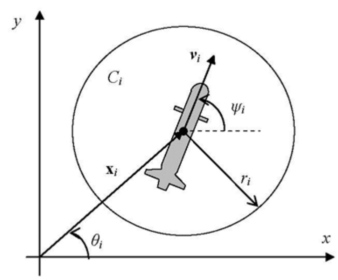
• The sensor is characterized by a field-of-view (FOV), represented by a discrete geometric object, and by a joint probability density or mass function (PDF or PMF):

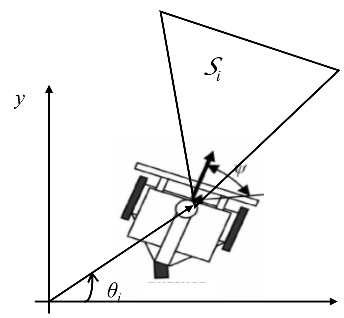
$$p(z_k,\xi_k,\lambda_k) = p(z_k \mid \xi_k,\lambda_k)p(\xi_k)p(\lambda_k)$$ **Probabilistic measurement model**

• The vehicle is characterized by a discrete geometric object and a dynamic equation.

$$\dot{x}(t) = f[x(t),u(t),w(t),t]$$ **Vehicle equation of motion**

Examples:





3

LISC
LABORATORY FOR INTELLIGENT SYSTEMS AND CONTROLS

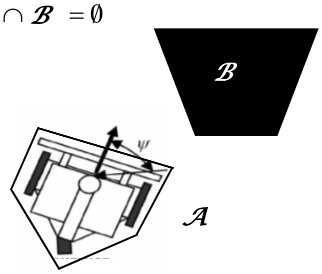
Duality of Sensor and Robot Path Planning

• In classical robot path or motion planning, a discrete geometric object $\mathcal{A}$ (the robot) must avoid intersections (collisions) with multiple objects (obstacles) $\mathcal{B}_1$, $\mathcal{B}_2$, …

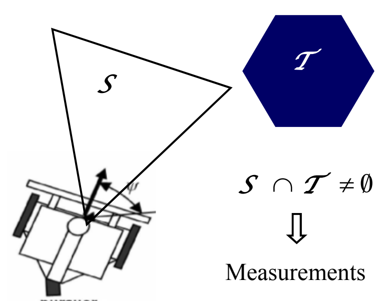
• In sensor path planning, a discrete geometric object S (the sensor's FOV) must intersect (measure) multiple objects (targets) $\mathcal{T}_1$, $\mathcal{T}_2$, …

Robot path planning:

$\mathcal{A} \cap \mathcal{B} = \emptyset$



Sensor path planning:



Kinodynamic model: $\dot{\mathbf{x}}(t) = \mathbf{f}[\mathbf{x}(t),\mathbf{u}(t),\mathbf{w}(t),t]$

4

LISC
LABORATORY FOR INTELLIGENT SYSTEMS AND CONTROLS

Sensing Performance Function

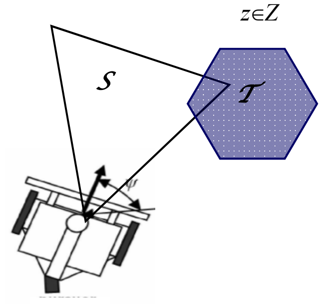
The sensor classification performance, typically, is not available in closed-form.

Target Information Value or *Information Gain*:

Expected Entropy Reduction (EER) [Cai, Ferrari 2007] [§]

$$\Delta H(\xi; z \mid \lambda) \equiv H(\xi \mid \lambda) - \sum_{z \in Z} [H(\xi \mid \lambda, z) p(z \mid \lambda)]$$

Advantage: additive, symmetric, non-myopic, ..



$\mathcal{S} \cap \mathcal{T} \neq 0 \Rightarrow$ Measurements, z

§ G. Zhang, S. Ferrari, and C. Cai, "A Comparison of Information Functions and Search Strategies for Sensor Planning in Target Classification," *IEEE Transactions on Systems, Man, and Cybernetics - Part B*, in press.

5

LISC
LABORATORY FOR INTELLIGENT SYSTEMS AND CONTROLS

Information-driven Sensor Path Planning

Ground mobile sensors for fixed target classification
- ✓ Cell decomposition
- ✓ Information potential function
- ✓ Probabilistic information roadmap method

Ground mobile sensors for target tracking and surveillance
- ✓ Particle filter-based method
- ✓ Disjunctive programming

Underwater mobile sensors for cooperative target tracking
- ✓ Optimal control

Air mobile sensor deployed for fixed target detection and classification
- ✓ Approximate dynamic programming (ADP)

Air and ground sensors for target detection, tracking, localization, and pursuit
- ✓ Cell decomposition, probabilistic roadmap method, and particle filter-based method

Computer games (CLUE, Ms. Pacman, and Marco Polo)
- ✓ Cell decomposition
- ✓ Influence diagrams
- ✓ Reinforcement learning, and ADP

6

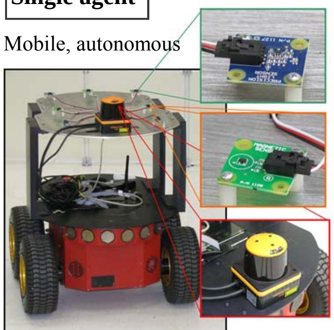
LISC
LABORATORY FOR INTELLIGENT SYSTEMS AND CONTROLS

Application Example

Indoor Monitoring and Surveillance

Single agent

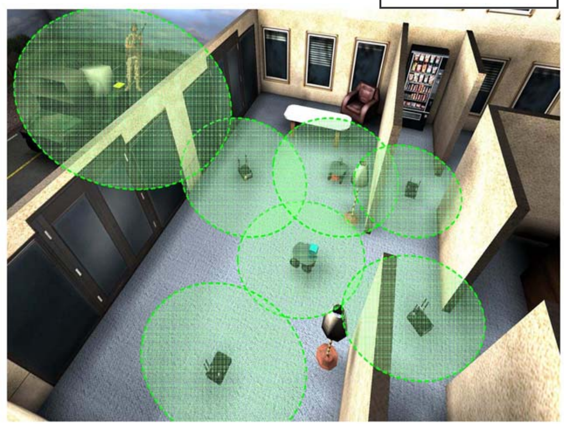
Mobile, autonomous



Wireless communication

Sensors

Multiple agents

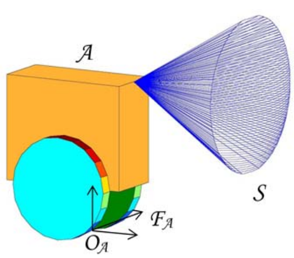


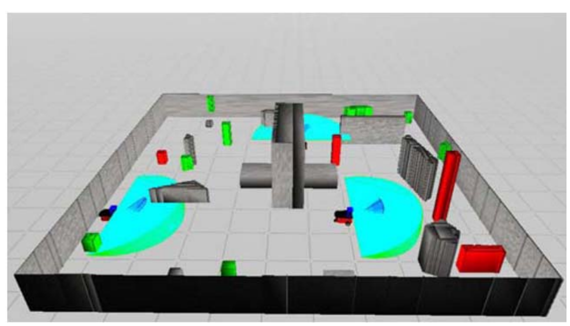
7

LISC
LABORATORY FOR INTELLIGENT SYSTEMS AND CONTROLS

Treasure Hunt Problem

For a given layout $\mathcal{W} \subset \Re^3$ with r targets and n obstacles and a given joint probability mass function p(z, ξ, λ), find the obstacle-free path that minimizes the distance traveled by a robot $\mathcal{A}$ between two configurations q_0 and q_f, and maximizes the total information value, for a sensor with field-of-view $\mathcal{S}$, installed on $\mathcal{A}$.



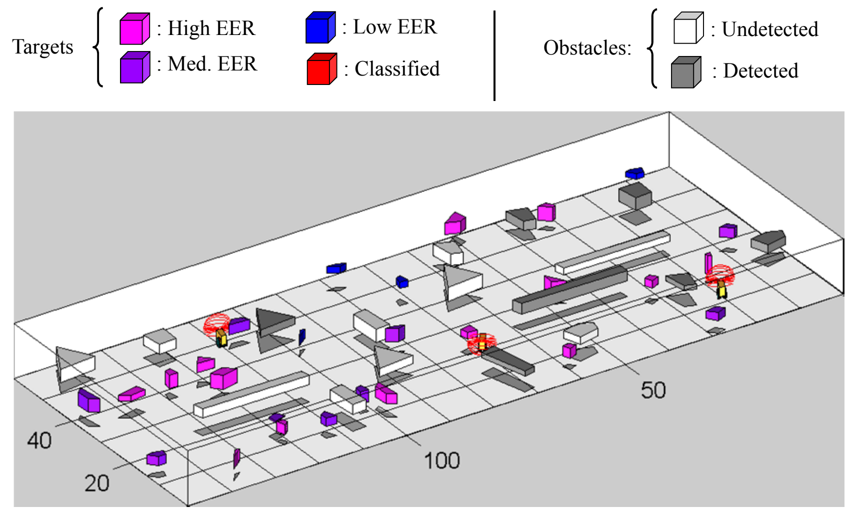


8

S. Ferrari and C. Cai, "Information-Driven Search Strategies in the Board Game of CLUE®," *IEEE Transactions on Systems, Man, and Cybernetics - Part B*, Vol. 39, No 3, June 2009.

LISC
LABORATORY FOR INTELLIGENT SYSTEMS AND CONTROLS

Multiple Sensors, Multiple Targets

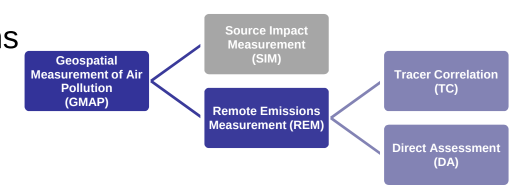


Sensors must also avoid collisions with other moving sensors, based on knowledge of their instantaneous configuration.

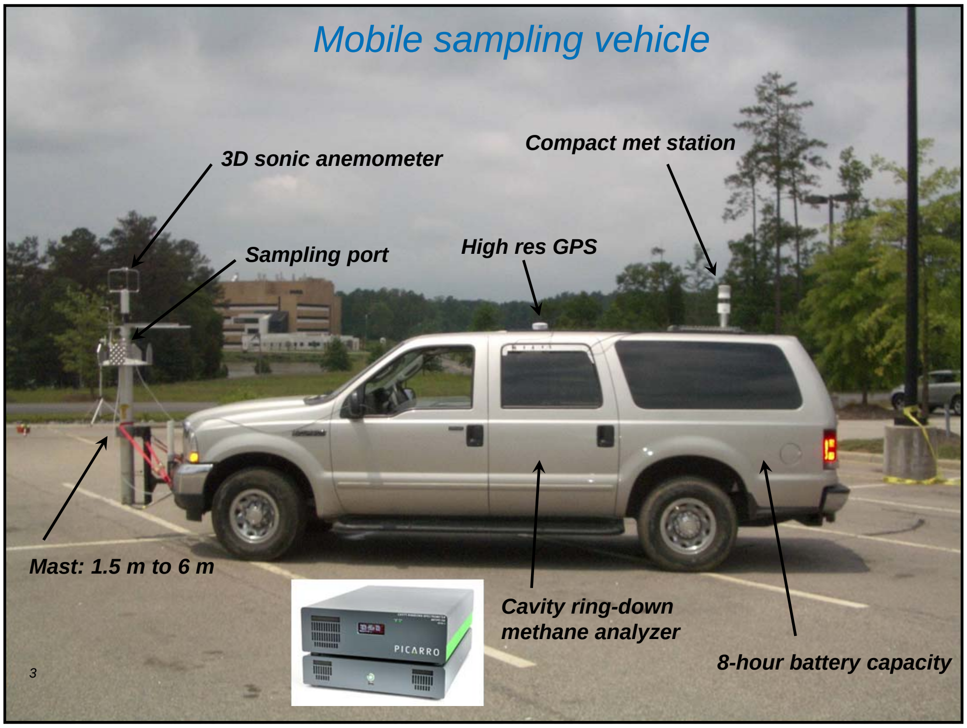
EPA United States Environmental Protection Agency

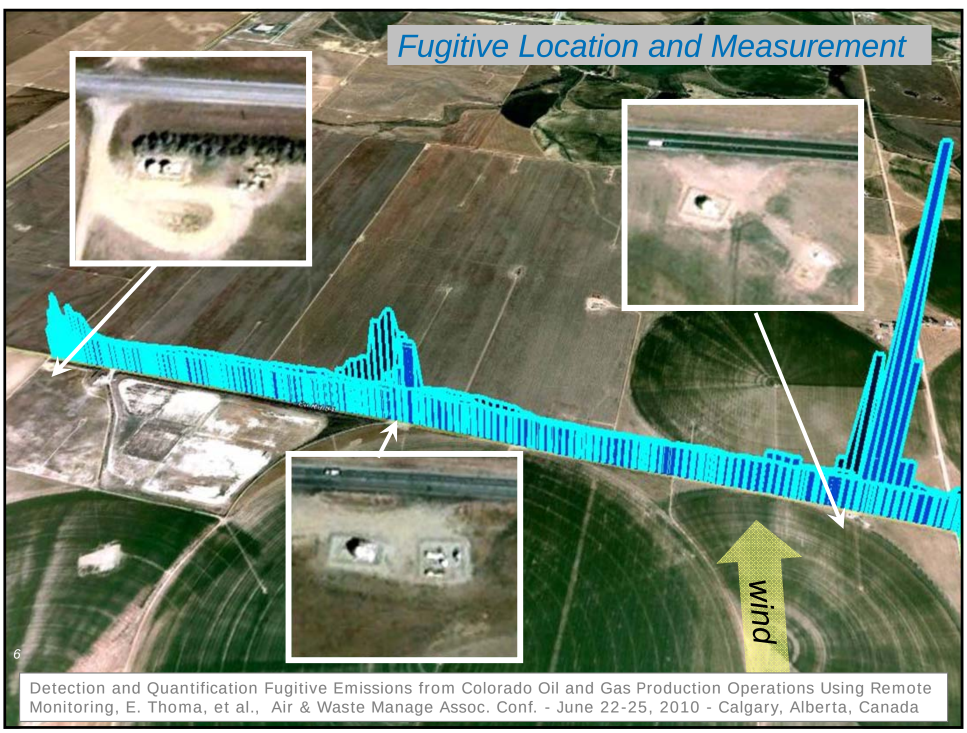
GMAP Remote Emissions Measurement

GMAP-REM Concept:
Detect and quantify emissions of a specific species from a large area or distributed source via mobile sampling and plume dispersion diagnostics.



Example projects:
1. Detection of methane emissions from distributed oil and gas production wells using a Direct Assessment (DA) approach
2. Quantification of methane emissions from landfills using an acetylene tracer via the Tracer Correlation (TC) approach

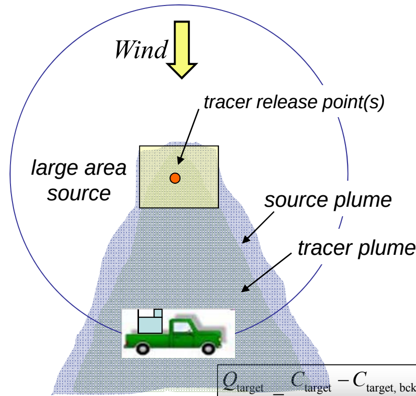

Mobile sampling vehicle
3D sonic anemometer
Compact met station
Sampling port
High res GPS
Mast: 1.5 m to 6 m
Cavity ring-down methane analyzer
8-hour battery capacity
PICARRO
3


Fugitive Location and Measurement
wind
6
Detection and Quantification Fugitive Emissions from Colorado Oil and Gas Production Operations Using Remote Monitoring, E. Thoma, et al., Air & Waste Manage Assoc. Conf. - June 22-25, 2010 - Calgary, Alberta, Canada

EPA United States Environmental Protection Agency

Large area source measurements GMAP REM TC

- Release tracer gas from strategic locations within the facility
- Use mobile sampling platform to map target source and tracer plumes
- Calculate dilution ratio based on known tracer rate
- EPA method development research
  Waste Management CRADA #372-A-08, EP-C-07-15 WA 2-10



$$\frac{Q_{\text{target}}}{Q_{\text{tracer}}} = \frac{C_{\text{target}} - C_{\text{target, bckgnd}}}{C_{\text{tracer}} - C_{\text{tracer, bckgnd}}}$$

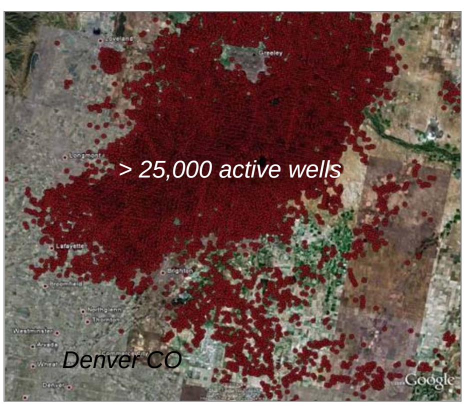
Quantifying Methane Fluxes Simply and Accurately, The Tracer Dilution Method, C. W. Rella, E. R. Crosson, et al. European Geophysical Union Meeting, 2–7 May 2010, Vienna, Austria.

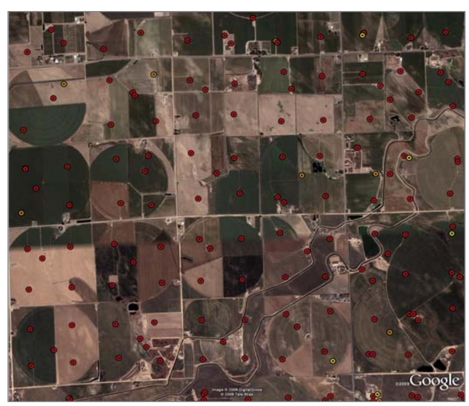
Methane Emissions at Nine Landfill Sites in the Northeastern United States, B.W. Mosher, P.M. Czepiel, et al. Environ. Sci. Technol. 1999, 33, 2088–2094.

Measurements of Methane Emissions from Landfills Using a Time Correlation Tracer Method Based on FTIR Absorption Spectroscopy, B. Galle, B.; J. Samuelsson, et al. Environ. Sci. Technol. 2001, 35, 21-25.

EPA United States Environmental Protection Agency

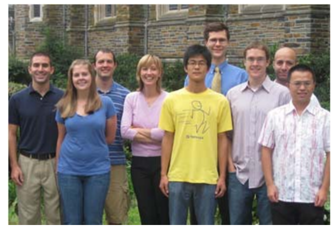
Oil and gas production: distributed sources





LISC
LABORATORY FOR INTELLIGENT SYSTEMS AND CONTROLS

Acknowledgements



LISC Students:
Wenjie Lu, IGERT Associate
Ashleigh Swingler, IGERT Fellow
Greg Foderaro
Keith Rudd, IGERT Fellow
Hongchuan Wei, IGERT Associate
Xu Zhang

New Class of IGERT Fellows:
Cassi Carley, Computer Science
Tierney Foster-Wittig, Civil and Environmental Engineering
Matthew Ross, Biology (Ecology) and Nicholas School of the Environment
Weston Ross, Mechanical Engineering and Materials Science
Patrick Wang, Electrical and Computer Engineering
Tiffany Wilson, Civil and Environmental Engineering

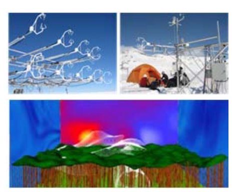
Sponsors:

This research is funded by NSF grant DGE-1068871

15

Duke | Wireless Intelligent Sensor Networks
IGERT WISeNet

WISeNet Graduate Training at Duke



WISeNet trainees contribute to the development of intelligent sensor systems that process, store, and learn from data so as to improve their ability to gather information over time. By participating in WISeNet laboratory and field experiments, trainees also contribute first hand to unprecedented observations of environmental and ecological processes, and more effective and reliable use of sensors for defense and national security.

WISeNet is currently accepting applications

Trainees must be enrolled in a Ph.D. program in one of the participating departments at Duke University. Duke students who are interested in applying should request application material from the WISeNet Program Director, Prof. Silvia Ferrari (Email: webmaster@lisc.pratt.duke.edu). Non-Duke students interested in WISeNet are strongly encouraged to apply to the graduate program of interest through Duke Graduate School (http://gradschool.duke.edu/admissions/).

For more information visit: **http://wisenet.pratt.duke.edu/**

IGERT

Pratt School of Engineering | Nicholas School of the Environment
Trinity College of Arts & Science | Duke University

References

S. Ferrari, R. Fierro, and T. A. Wettergren, *Modeling and Control of Dynamic Sensor Networks*, CRC Press, Boca Raton, FL, ISBN 1439866791, scheduled to appear December 2012.

•S. Ferrari, G. Zhang, and C. Cai, "A Comparison of Information Functions and Search Strategies for Sensor Planning," *IEEE Transactions on Systems, Man, and Cybernetics - Part B*, Vol. 42, No. 1, 2012.

•N. Bezzo, R. Fierro, A. Swingler, and S. Ferrari, "Mobile Router Networks: A Disjunctive Programming Approach," *International Journal of Robotics and Automation*, Vol. 26, No. 1, pp.13-25, 2011.

S. Ferrari and G. Daugherty, "A Q-Learning Approach to Online Unmanned Air Vehicle (UAV) for Target Detection and Classification," *Journal of Defense Modeling and Simulation*, Vol. 9, pp. 83-92, 2011.

G. Foderaro, V. Raju, and S. Ferrari, "A Model-based Approximate λ-Policy Iteration Approach to Evasive Path Planning and the Video Game Ms. Pac-Man," *Journal of Control Theory and Applications*, Vol. 9, No. 3, pp. 391-399, 2011.

•S. Ferrari, G. Zhang, and T. A. Wettegren, "Probabilistic Track Coverage in Cooperative Sensor Networks," *IEEE Transactions on Systems, Man, and Cybernetics – Part B*, Vol. 40, No. 6, pp.1492-1504, 2011.

W. Lu, G. Zhang, S. Ferrari, R. Fierro, and I. Palunko "An Improved Particle Filter Approach for Multiple Target Detection and Tracking," *Proc. SPIE Conference*, Orlando, FL, 2011.

S. Ferrari, G. Foderaro, and A. Tremblay "A Probability Density Function Approach to Distributed Sensors Path Planning," *Proc. IEEE Conference on Robotics and Automation*, Anchorage, AK, 2010.

S. Ferrari and G. Foderaro, "A Potential Field Approach to Finding Minimum-Exposure Paths in Wireless Sensor Networks," *Proc. IEEE Conference on Robotics and Automation*, Anchorage, AK, 2010.

A. Swingler and S. Ferrari, "A Cell Decomposition Approach to Cooperative Path Planning and Collision Avoidance," *Proc. IEEE Conference on Decision and Control*, Atlanta, GA, 2010.

References

B. Bernard and S. Ferrari, "A Geometric Transversals Approach to Track Coverage of Maneuvering Targets," *Proc. IEEE Conference on Decision and Control*, Atlanta, GA, 2010.

G. Foderaro and S. Ferrari, "Necessary Conditions for Optimality for a Distributed Optimal Control Problem," *Proc. IEEE Conference on Decision and Control*, Atlanta, GA, 2010.

W. Lu, G. Zhang, and S. Ferrari, "A Randomized Hybrid System Approach to Coordinated Robotic Sensor Planning," *Proc. IEEE Conference on Decision and Control*, Atlanta, GA, 2010.

S. Ferrari and G. Daugherty, "A Q-Learning Approach to Online Unmanned Air Vehicle (UAV) for Target Detection and Classification," *Proc. SPIE Conference*, Orlando, FL, April 2010.

•K. C. Baumgartner, S. Ferrari, and T. A. Wettergren, "Robust Deployment of Ocean Sensor Networks," *IEEE Sensors Journal*, Vol. 9, No. 9, pp. 1029-1048, 2009.

•K. C. Baumgartner, S. Ferrari, and A. Rao, "Optimal Control of a Mobile Sensor Network for Cooperative Target Detection," *IEEE Journal of Oceanic Engineering*, Vol. 34, No. 4, pp. 678-697, 2009.

•G. Zhang, S. Ferrari, and M. Qian, "Information Roadmap Method for Robotic Sensor Path Planning," *Journal of Intelligent and Robotic Systems*, Vol. 56, pp. 69-98, 2009.

•S. Ferrari, R. Fierro, B. Perteet, C. Cai, and K. C. Baumgartner, "A Multi-Objective Optimization Approach to Detecting and Intercepting Dynamic Targets using Mobile Sensors, " *SIAM Journal on Control and Optimization*, Vol. 48, No. 1, pp. 292-320, 2009.

S. Ferrari and C. Cai, "Information-Driven Search Strategies in the Board Game of CLUE®," *IEEE Transactions on Systems, Man, and Cybernetics - Part B*, Vol. 39, No. 3, pp. 607-625, June 2009.

C. Cai and S. Ferrari, "Information-Driven Sensor Path Planning by Approximate Cell Decomposition," *IEEE Transactions on Systems, Man, and Cybernetics - Part B*, Vol. 39, No. 3, pp. 672-689, June 2009.

LISC
LABORATORY FOR INTELLIGENT SYSTEMS AND CONTROLS

References

- S. Ferrari, "Multi-Objective Algebraic Synthesis of Neural Control Systems by Implicit Model Following," *IEEE Transactions on Neural Networks*, Vol. 20, No. 3, pp. 406-419, March 2009.

S. Ferrari, R. Fierro, and D. Tolic, "A Geometric Optimization Approach to Tracking Maneuvering Tracking Using a Heterogeneous Mobile Sensor Network," *Proc. IEEE Conference on Decision and Control*, Shanghai, China, December 2009.

G. Zhang and S. Ferrari, "An Adaptive Artificial Potential Function Approach for Geometric Sensing," *Proc. IEEE Conference on Decision and Control*, Shanghai, China, December 2009.

G. Di Muro and S. Ferrari, "Penalty Function Method for Exploratory Adaptive-Critic Neural Network Control," *Proc. Mediterranean Conference on Control and Automation (MED'09)*, Thessaloniki, Greece, January 2009, pp. 1410-1414.

D. Tolic, R. Fierro, and S. Ferrari, "Cooperative multi-target tracking via hybrid modeling and geo- metric optimization," *Proc. Mediterranean Conference on Control and Automation (MED'09)*, Thessaloniki, Greece, January 2009, pp. 440-445.

- Ferrari S., Steck J. E, and Chandramohan R., "Adaptive Feedback Control by Constrained Approximate Dynamic Programming," *IEEE Transactions on Systems, Man, and Cybernetics - Part B: Cybernetics*, Vol. 38, No. 4, pp. 982-987, August 2008.

Baumgartner, K. C., and Ferrari, S., "A Geometric Approach to Analyzing Track Coverage in Sensor Networks", *IEEE Transactions on Computer*, Vol. 57, No. 8, pp. 1113-1128, August 2008.

S. Ferrari and A. Vaghi, "Demining Sensor Modeling and Feature-level Fusion by Bayesian Networks," *IEEE Sensors Journal*, Vol. 6, No. 2, pp. 471-483, April 2006.

PDFs AVAILABLE UPON REQUEST: sferrari@duke.edu