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NSF IGERT: Wireless Intelligent Sensor Networks WISeNet

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

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Guidance and Control of Mobile Sensors

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..)

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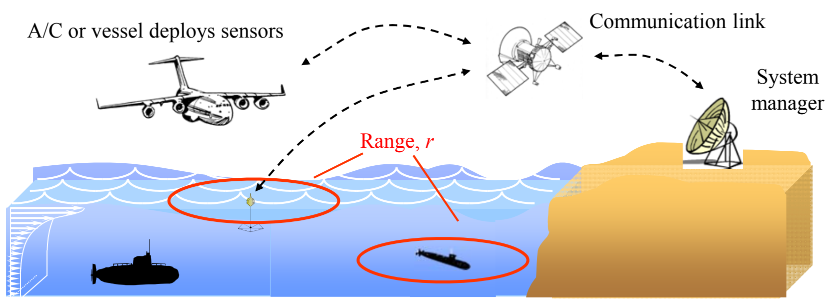
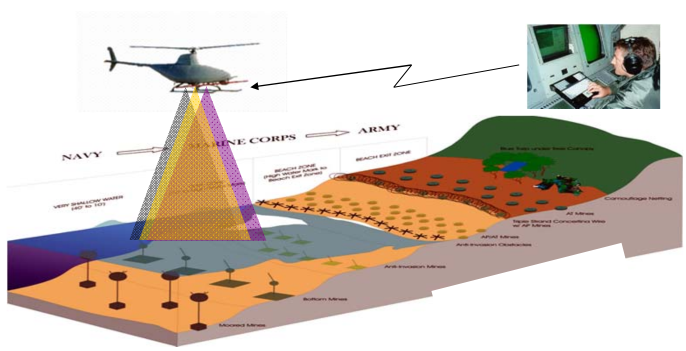
Undersea Surveillance



- Sensors: acoustic, w./ GPS, limited micro-level processing, mobile
- Targets: passive, mobile, unauthorized
- Environment: heterogeneous bathymetry and ambient properties, currents
- Sensing objectives: coverage, tracking, detection, classification

UAV Demining

BAE SYSTEMS



- Sensors: Cameras, IR, GPR, EMI, synthetic aperture radar (SAR)
- Targets: static, hidden, hazardous
- Environment: heterogeneous soils, weather, time of day, obstacles
- Sensing objectives: detection, classification

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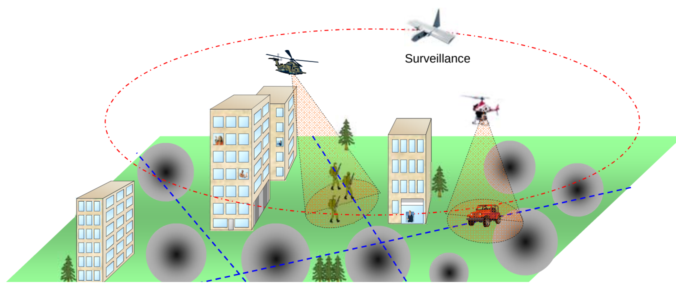
Urban Monitoring



- Sensors: Cameras, IR, synthetic aperture radar (SAR)
- Targets: static, hidden, mobile, evading
- Environment: time of day, obstacles
- Sensing objectives: detection, classification, tracking

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Sensor Model

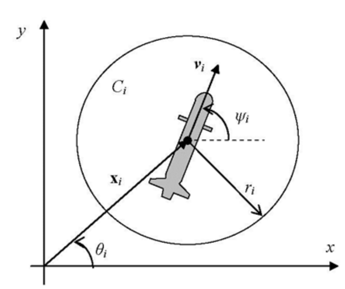
• The sensor is characterized by a field-of-view (FOV), represented by a discrete geometric object, and by a joint probability density or mass function (PDF or PMF):

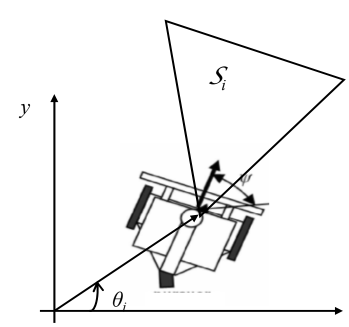
$$p(z_k,\xi_k,\lambda_k) = p(z_k \mid \xi_k,\lambda_k)p(\xi_k)p(\lambda_k)$$ **Probabilistic measurement model**

• 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:





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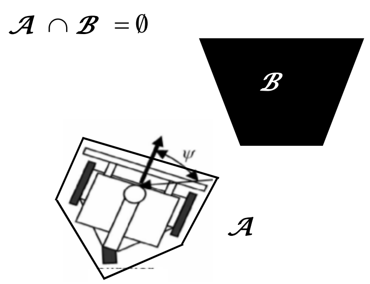
Duality of Sensor and Robot Path Planning

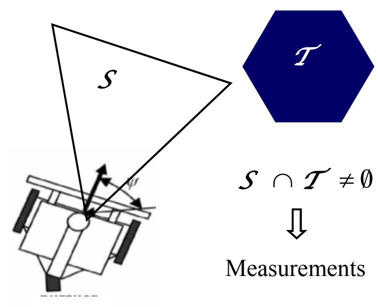
- In classical robot path or motion planning, a discrete geometric object $\mathcal{A}$ (the robot) must avoid intersections (collisions) with multiple objects (obstacles) $\mathcal{B}_1$, $\mathcal{B}_2$, …

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

Robot path planning:



Sensor path planning:



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

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Sensing Performance Function

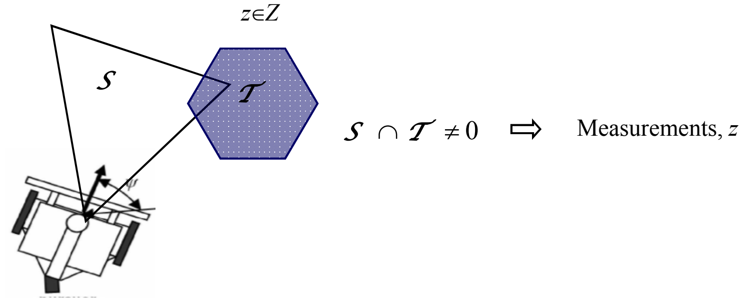
The sensor classification performance, typically, is not available in closed-form.

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, ..



§ 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.

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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

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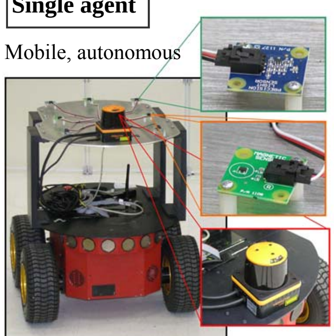
Application Example

Indoor Monitoring and Surveillance

Single agent

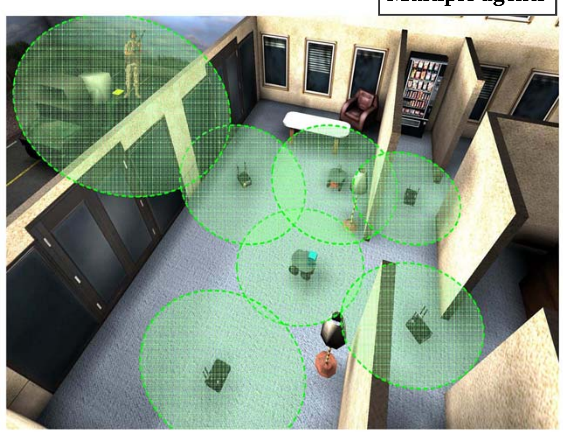
Mobile, autonomous



Wireless communication

Sensors

Multiple agents



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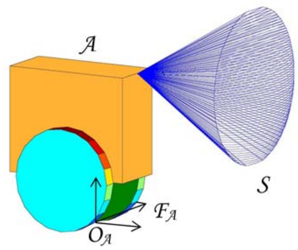
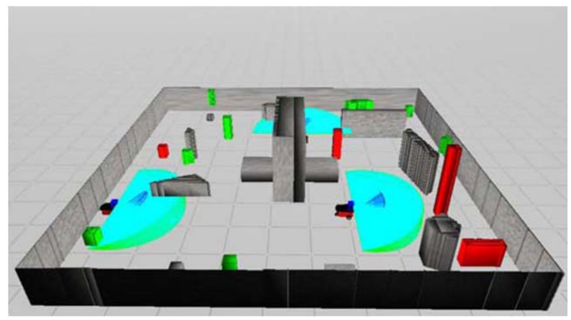
Treasure Hunt Problem

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 $\mathcal{A}$.





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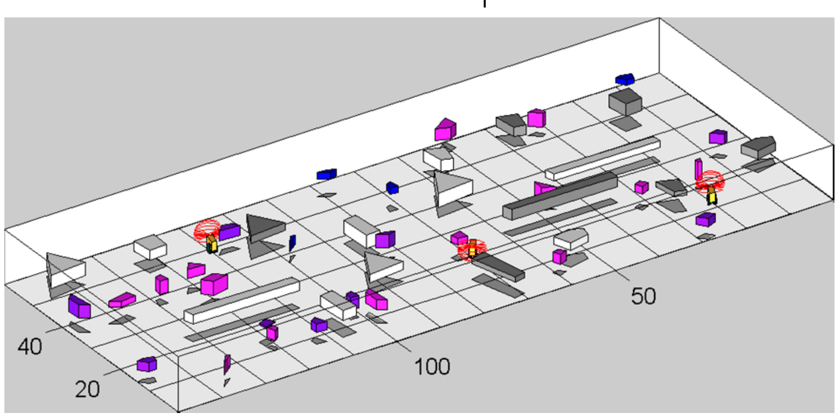
Multiple Sensors, Multiple Targets

Targets: : High EER; : Med. EER; : Low EER; : Classified

Obstacles: : Undetected; : Detected



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

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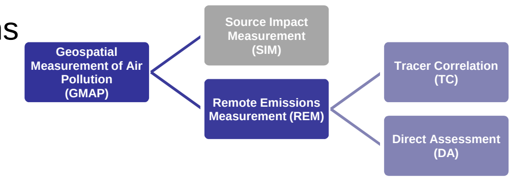
United States Environmental Protection Agency

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

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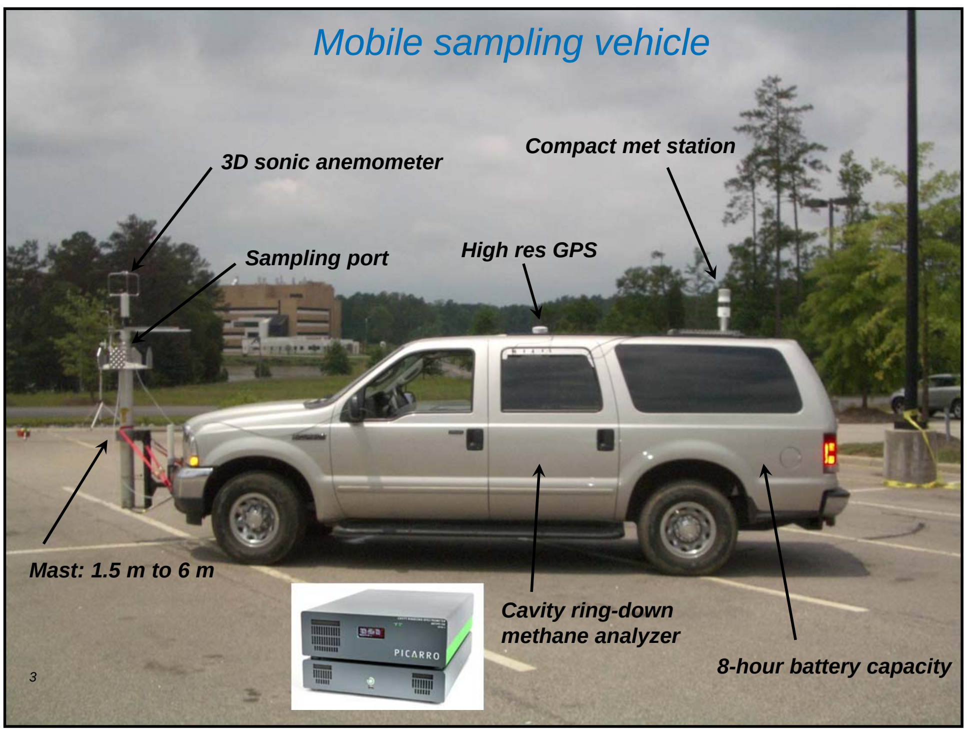
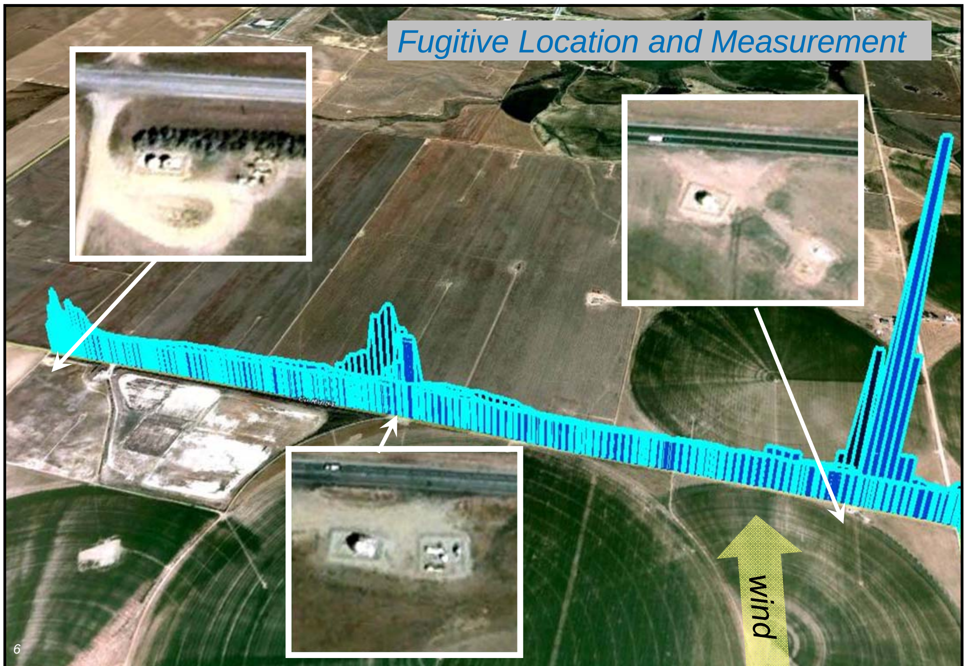


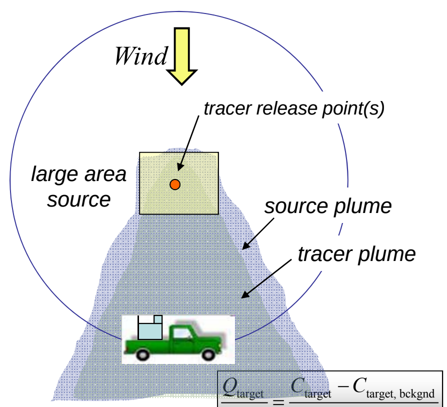


Detection and Quantification Fugitive Emissions from Colorado Oil and Gas Production Operations Using Remote Monitoring, E. Thoma, et al., Air & Waste Manage Assoc. Conf. - June 22-25, 2010 - Calgary, Alberta, Canada

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



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

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.

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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.

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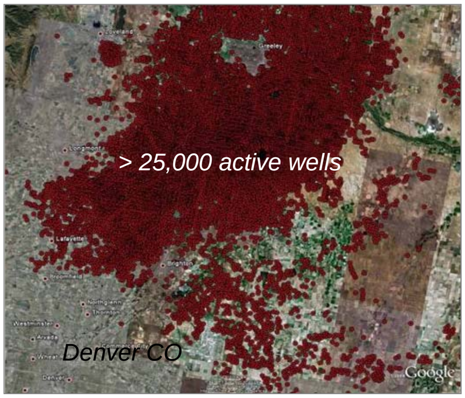
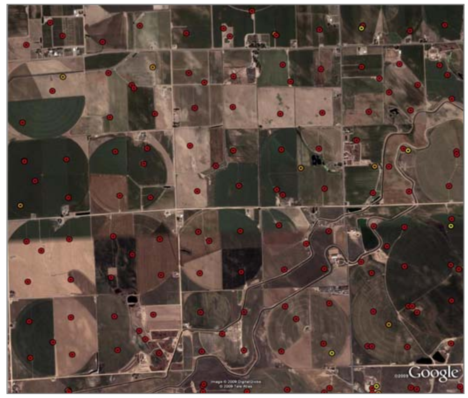
EPA United States Environmental Protection Agency

Oil and gas production: distributed sources





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Hongchuan Wei, IGERT Associate
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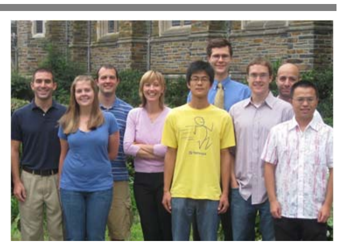

New Class of IGERT Fellows:
Cassi Carley, Computer Science
Tierney Foster-Wittig, Civil and Environmental Engineering
Matthew Ross, Biology (Ecology) and Nicholas School of the Environment
Weston Ross, Mechanical Engineering and Materials Science
Patrick Wang, Electrical and Computer Engineering
Tiffany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

Sponsors:

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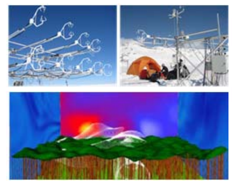
WISeNet Graduate Training at Duke

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/**

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WISeNet Team

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1) **PIs (Duke University):**
- Silvia Ferrari (Mechanical Engineering, Sec.: ECE, CS, DIBS)
- John Albertson (Civil and Environmental Engineering, Sec: NSOE)
- Gabriel Katul (NSOE, Sec: CEE)
- Ron Parr (Computer Science)
- Pankaj Agarwal (Computer Science, Sec: Math)

2) **International Participants**
- Nicola Montaldo, University of Cagliary, Italy
- Lorenzo Marconi, University of Bologna, Italy
- Marc Parlange, EPFL, Switzerland
- Marco Marani, University of Padova, Italy
- Martin McGinnity, ISRC, University of Ulster, Ireland

3) **Partners from Industry and Government Laboratories**
- Caryl Johnson, Fellow, British Aerospace (BAE), Honolulu (HI)
- Gayle Hagler, Research Scientist, US Environmental Protection Agency (EPA), Raleigh (NC)
- Thomas Wettergren, US Navy Senior Technologist, Naval Undersea Warfare Center (NUWC), Newport (RI)

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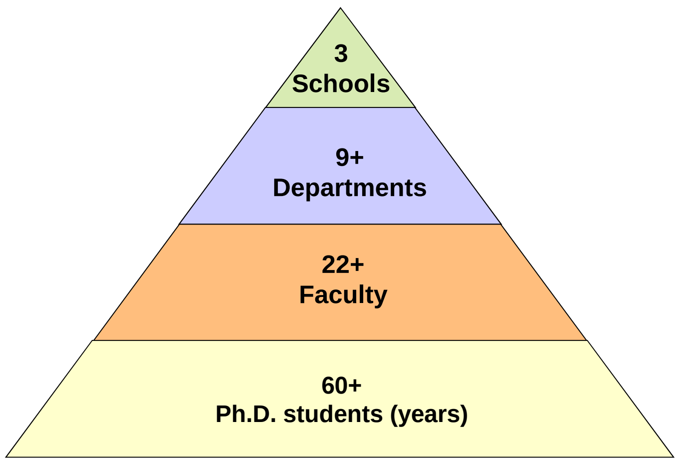
WISeNet by the Numbers



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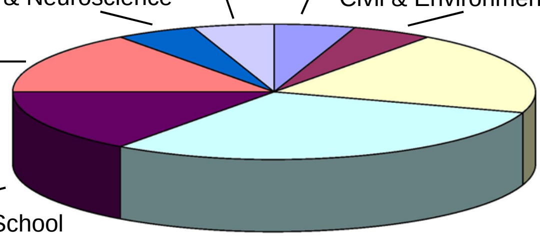
Faculty and Student Distribution by Department



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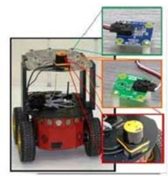
WISeNet Research Areas

1) Information-Driven Environmental Sensing and Prediction
- Distributed sensor management
- Ecosystem and eco-hydrological dynamic modeling and prediction
- Climate-change impacts on terrestrial ecosystems and seasonal snow cover



2) Guidance and Control of Mobile Sensor Networks
- Autonomous vehicles with onboard sensors and wireless communications
- Integrated sensor feedback control and signal processing (active sensing)
- Intelligent control and coordination of heterogeneous sensor networks

3) Biologically-Inspired Intelligent Sensor Systems
- Rapidly coordinate movement, while integrating sensor information
- Adaptation and learning
- Transform sensory inputs into appropriate motor outputs
- Design biologically-inspired artificial robotic sensors

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WISeNet Menu of Laboratory and Field Experiments

1) **Drought Monitoring and Prediction in Semiarid Climates** (Sardinia, Italy)
- J. D. Albertson (Duke) and N. Montaldo (Uni. Cagliari)

2) **Alpine Search-and-Rescue Operations** (CASY, Bologna)
- L. Marconi (Uni. Bologna)

3) **Sea-level Rise Mitigation and Adaptation Measures** (Venice Lagoon)
- M. Marani (Uni. Padova)

4) **Modeling and Prediction of Climate Impacts on Snow/Ice** (Swiss Alps)
- M. Parlange (EPFL)

5) **Geospatial Monitoring of Air Quality and Pollutants** (EPA, NC**,** USA)
- G. Hagler (EPA)

6) **Intelligent Robotic Games** (ISRC, University of Ulster, Ireland, UK)
- M. McGinnity (ISRC)

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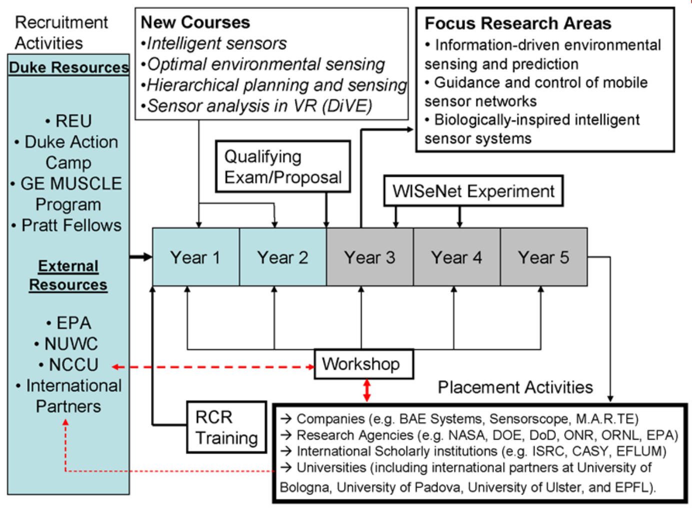
WISeNet Graduate Training At-a-Glance



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