Mobile and Robotic Sensor Systems for Environmental Monitoring

Overall Course Conclusion
Outline

• Motivation
  – Air and water quality monitoring
  – Environmental sensing

• Mobile sensor systems
  – The OpenSense project

• Robotic sensor systems
  – Examples of robotic sensor systems for oceanography and limnology

• Overall conclusions of the course
Motivation
Motivation for Spatially Dense Air Quality Monitoring

Air pollution in urban areas is a global concern
  • affects quality of life and health
  • urban population is increasing

Air pollution is highly location- and time-dependent
  • traffic chokepoints and rush hours
  • urban canyons and weather
  • industrial installations and activities

Air pollution monitoring today
  • Sparse, stationary and expensive stations
  • Spatial interpolation with mesoscale models
Motivation for Spatially Dense Water Quality Monitoring

Fresh water quality monitoring is a global concern
- Fresh water reservoirs are under pressure
- Global population is increasing
- Water ecosystems are not well understood

Water quality is location- and time-dependent
- natural transport phenomena, weather
- interaction lake physics and biology
- waste treatment plants, industrial installations, agricultural activities

Water quality monitoring today
- Stationary research stations leveraging vertical profilers
- Operational boats equipped with dedicated sensing equipment
Environmental Monitoring

Typical solution in environmental monitoring:
- sparse sensing
- expensive
- field estimation via models
- possible mobility

Distributed solution for augmentation:
- size, cost
- number
- networked
- mobile

Physical field:
- built or natural
- bounded or unbounded
- 2D or 3D
Air Quality Monitoring
Importance of Air Quality

On March 25, 2014, the WHO reported:

“... in 2012 around 7 million people died – one in eight of total deaths – as a result air pollution exposure. This finding more than doubles previous estimates and confirms that air pollution is now the world’s largest single environmental health risk.”

“The new estimates are not only based on more knowledge about the diseases caused by air pollution, but also upon better assessment of human exposure to air pollutants through the use of improved measurements and technology.”

Satellite-based remote sensing

Examples:
• Measurements of Pollution in the Troposphere (MOPITT on Terra satellite)
• Ozone Measurement Instrument (OMI on Aura satellite)

Features:
• daily scans
• large coverage
• homogeneous quality
• sensitive to cloud coverage
• low resolution
Monitoring Today

Stationary and expensive stations

Sparse sensor network (Nabel)

Expensive mobile high fidelity equipment

Coarse models (mesoscale = 1km²)

Personal exposure with specialized punctual studies

1 Garage
2 Vehicle
3 Road
4 Indoor
Explorative Efforts in Dense Sensing

- **Examples of private sector initiatives**
  - AirQualityEgg by Wicked Device;
  - Laser Egg by Kai Terra;
  - Clarity Nodes by Clarity;
  - Airlib by Rimalu Technologies

- **Examples of city initiatives**
  - Massive deployment of stations (150) at street-level (2008/2009 New York City Community Air Quality Survey);
  - Bloomberg Philanthropies with city of Paris: 150 Clarity nodes (PM 2.5/NO2) around schools with involvement of AirParif (2019)
  - Breathe London: 100 stationary nodes, two Google Street View cars, wearable sensors for children (2019)

- **Examples of research initiatives**
The OpenSense Project
OpenSense Vision

Measurement data
Citizen-, consortium-, agency-operated sensors

Explanatory Variables
Land-use, meteorology, traffic

Exposure information
Personal recommendations, health studies, urban planning, crowdsensing

High-resolution pollution maps
Spatiotemporally flexible, modeling; emphasis on data-driven statistical modeling methods
OpenSense Sensing Platform (Lausanne Deployment)

- Mission: measure **gas-phase pollutants** (CO, NO₂, O₃, CO₂), **particulate matter** (PM), temperature and humidity

- Gases:
  - mix of small, relatively **low cost**, electrochemical, metal oxide, and optical sensors.
  - **slow response time; need re-calibration; cross-sensitive (low selectivity)**

- Particles:
  - physical metrics: Lung-Deposited Surface Area (LDSA)
  - **nanoscale sensitivity** (<100 nanometers)
  - **high cost**

- **Mobility energy**: leverage public transportation vehicles!
- **Connectivity**: leverage GPRS since no significant energy limitations!
Enable high spatio-temporal resolution monitoring of urban air quality through mobile wireless sensor networks.

Overview

- **System Design**
  - Modular & flexible
  - Using low-cost sensors

- **Mobility Effects**
  - Slow sensor response
  - Mitigation approaches

- **Calibration**
  - Novel model-based & mobility-aware approaches

- **Mapping**
  - Novel statistical techniques
  - Heterogeneous data sources

[Arfire, EPFL PhD thesis, 2016]
Contributors: Adrian Arfire, Emmanuel Droz, Alexander Bahr, Julien Eberle (LSIR-EPFL), Ali Marjovi, Christophe Paccolat
Sensor Node Design

Data logging & Communication  Localization

Air Sampling
Gas Sampler  PM Sampler

CAN Bus
The Sensor Network

In the field

- 10 Lausanne buses
- Static deployment at NABEL site for calibration & testing
- Electric vehicle node for targeted research

Server-side

- Diagnosis server
- Back-end server
- Front-end server
- End-users

[EBERLE, EPFL PhD thesis 2016]
System Performance

Data throughput

Deployment start: October 22, 2013 (~ 3 years), numerical values on Sep 28, 2016

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Sampling rate</th>
<th># of measurements</th>
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</thead>
<tbody>
<tr>
<td>LDSA (PM)</td>
<td>1 s</td>
<td>&gt; 203 million</td>
</tr>
<tr>
<td>[CO, NO₂, CO₂]</td>
<td>5 s</td>
<td>&gt; 101 million</td>
</tr>
<tr>
<td>[O₃, temp., RH]</td>
<td>5 s</td>
<td>&gt; 71 million</td>
</tr>
<tr>
<td>GPS fix</td>
<td>1 s</td>
<td>&gt; 325 million</td>
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<tr>
<td>[odometer, accelerometer]</td>
<td>0.25 s</td>
<td>&gt; 1352 million</td>
</tr>
<tr>
<td>vehicle context info</td>
<td>event-driven</td>
<td>&gt; 14 million</td>
</tr>
</tbody>
</table>

- [Arfire et al., in preparation]
Contributors: Adrian Arfire, Ali Marjovi
Mobility Effect

• Except for work in robot olfaction, largely unaddressed

Strategies:
• Limiting robot velocity
• Cycling between movement & stationary measurement
• Customized air sampling systems
Experimental Set-up

- Traversing system
- Sensor module
- Wind direction
- Smoke plume
- miniPID
Signal Reconstruction through Deconvolution

\[ s(t) \rightarrow h(t) \rightarrow r(t) \rightarrow g(t) \rightarrow \hat{s}(t) \]

- **s(t)**: True signal
- **h(t)**: Sensor model
- **r(t)**: Noise
- **g(t)**: Deconvolution filter
- **\( \epsilon(t) \)**: Noise
- **\( \hat{s}(t) \)**: Estimated signal

Graph showing sensor reading vs position with reference, measured signal, and deconvolved signal.
Signal Reconstruction through Deconvolution

Results

- Consistent performance improvement
- Reduction of RMSE drops as the speed increases (SNR decreases)
Active Sampling System Design

**Actuation:** axial fans, diaphragm pumps
Air Sampling System Comparison

Results

- Best performance: **pump-based sniffers**
Outdoor Experimental Validation

[Arfire et al., AIM 2016, EWSN 2016]
Contributors: Ali Marjovi, Adrian Arfire, Loïc Frund, Fabrizzio Gonzales, Thomas Coral, Jonathan Giezendanner
Mapping Problem

- LDSA data is sparse
- Coverage of sensors is incomplete and dynamic

- Generating complete maps is a challenge.

Solution:
- Other sources of data is required
- Models are required to estimate the LDSA in locations/times of interest
Statistical Modeling - Overview

Measurement Data → Explanatory Variables → Spatio-temporal aggregation → Modeling method → Air pollution map

Proxy pollutants, weather, traffic, land-use, etc.

Linear regression, ANN, Gaussian Process regression, PGM, etc.
Explanatory Variables

Proxy-pollutant data (NABEL)

Meteorological data (MeteoSwiss)

Land-use data (Swisstopo & GEOSTAT)

Traffic count data (Transitec)
Pollution Map Example

Coverage extended to the regions where both land-use and traffic data is available.
Water Quality Monitoring
Monitoring Coral Reefs

- Automatically deploy sensors
  - To save energy
- Optimally place sensors
  - For improved sensing
- Communication between sensors and robot
  - For near real-time feedback

Note: underwater robots are also called Underwater Autonomous Vehicles (AUVs)

[From C. Detweiler, D. Rus et al, MIT]
Monitoring Coral Reefs – The AMOUR robot

- Easily deployed: 25.5 Kg, 0.86m
- Shallow water operation (over 50m)
- 5 500W thrusters
  - 1.3 m/s
- >500Wh Li-ion battery
  - 8km range
  - 6 hour typical operation time
- Vertical & horizontal orientation
- Adjustable buoyancy and balance
- On-board logging and sensing
  - Camera, depth, temperature, salinity, dissolved oxygen
- Acoustic, optical, & radio communication

[From C. Detweiler, D.Rus et al., MIT]
Monitoring Coral Reefs – TheAquaNodes

- Processor/Logging
  - LPC2148 60MHz ARM
  - SD Card
- Communications
  - Acoustic: 300b/s
  - Radio: 57kb/s on surface
  - Optical: 1Mb/s
- Sensors
  - Temperature, pressure, salinity, dissolved oxygen
  - Camera
  - Other digital and analog inputs
- Depth Adjustment
  - 0.5m/min

[From C. Detweiler, D.Rus et al., MIT]
Autonomous Surface Vehicle (ASV)

[Hitz et al, *IEEE RAM* 2012]

- ASV Lizhbeth
- Inland water monitoring (deployed in lake Zurich)
- Probe controlled by winch from surface to up to 20 m depth
- Limnological parameters measured (including temperature profile)
Multi-AUVs for Limnology

[SNSF Sinergia project, 2015-2019
Martinoli, Wueest, Ibelings; key personnel: Bahr, Schill]
SNSF Sinergia Project – A Mission Example

- Measuring within a thin stratified bacterial layer in Lake Cadagno (TI)
- Varying depth and thickness
- High resolution temperature measurements within the layer to capture bacterial activity
- Added value of an AUV in respect to traditional instruments (vertical profilers): assessment of horizontal variations of the bacterial layer
SNSF Sinergia Project –
The AUV and its Sensing Payload

Equipped with a suite of sensors including Turbidity, Chlorophyll and a High Resolution Fast \((20 \, \mu K, 400 \, Hz)\) Temperature Sensor
[Quraishi et al., ICRA 2018]
Conclusion
Take Home Messages

- The area of sensor systems and sensor networks is booming for all sort of applications
- A lot of these applications are directly concerning the natural and built environment
- They are characterized by various degree of mobility (manually deployable, parasitic mobility, or controlled mobility)
- Totally new, unprecedented, and often distributed instruments are developed in the research labs and are becoming available on the market via various start-ups
- Intelligent instruments are very powerful and characterized by an increased software complexity which offer new opportunities in terms of customization, automation, etc.
More on urban air pollution and the OpenSense project:

- OpenSense: http://opensense.epfl.ch
- Breathe London: https://www.breathelondon.org/
More on robotic sensor systems for environment:

- Aquatic microbial observing systems
  [https://robotics.usc.edu/~namos/index.html](https://robotics.usc.edu/~namos/index.html)
- Autonomous Undersea Vehicle Applications Center
  [https://auvac.org/](https://auvac.org/)
- Adapting sampling of oceans
  [https://www.princeton.edu/~dcs1/asap/](https://www.princeton.edu/~dcs1/asap/)
- Monitoring coral reefs:
Course Take Home Messages
(Intelligent) Instruments as Specialized Embedded Systems

- e-puck
- Vertex
- DISAL Arduino Xbee
- Sensorscope station
- Handheld Airborne Mapping System
What These Systems Share at their Core?

Sensing  
Processing  
Mobility  

Communication  

Processing  
Visualization  
Storing  

In-situ instrument  
Transportation channel  
Base station  

The goal of this course is to shed light on this process and blocks!
What Did We Cover?

- Fundamentals of computer science:
  - Basics of computer architecture
  - C programming consolidation (vs. Matlab)
  - C for embedded and real-time systems

- Fundamentals of signal processing:
  - Analog/digital signals, sampling and reconstruction
  - Time/frequency domains and transforms
  - Filters, converters

- Fundamentals of embedded systems:
  - Microprocessors, microcontrollers, memory
  - Sensors and actuators
  - Basic control and communication techniques and concepts
Our Main Objectives for This Course

This course should allow you:

• To become a **power user** of the **field instruments** in environmental engineering used nowadays (sensor networks, meteorological stations, data loggers, etc.) and in even more so in the future (exploratory and cleaning robots, robotic sensor systems, etc.)

• To transport your **domain knowledge** into **code** to be deployed into **programmable** instruments

• To **collaborate** more efficiently with other engineers (e.g., computer, electrical, mechanical)

• To cumulate additional background to attend, if any interest, courses of the specialization on **Environmental Monitoring and Modeling** including our course on **Distributed Intelligent Systems**
Thank you for your attention!