Distributed Intelligent Systems – W13 and W14: Distributed Sensing using Robotic Sensor Networks
Outline

• Robotic sensor networks: challenges and applications

• Robotic sensor networks for distributed search: a case study on odor source localization
  – Challenges and approach
  – Single robot algorithms
  – Multi-robot algorithms

• Robotic sensor networks for distributed coverage: a case study on turbine inspection
  – Challenges and approach
  – Reactive distributed algorithms
  – Deliberative distributed algorithms
Robotic Sensor Networks for Turbine Inspection
Robotic Inspection Systems

• Inspection of
  – Power machinery
    (Alstom inspection robotics)
  – Aircraft skins
    (Siegel & Gunatilake 1997)
  – Welding seams on ships
    (Sanchez, Vazquez & Paz 2005)

• Sensors
  – Eddy current
  – Ultra-sound
  – Vision
Case Study

- Turbine blade inspection
- Initiated by the NASA Glenn Center in 2003 (Wong & Litt 2004)
- Constraints
  - Extreme miniaturization
  - Limited communication
- Focus on multi-robot coordination rather than locomotion
- Up to 40 robots

[Correll, PhD thesis, 2007]
Miniaturization

• Size constraints render single robot approach infeasible
• Miniaturization implies constraints on
  – Energy
  – Computation
  – Sensor and actuator accuracy
  – Communication

System behavior essentially probabilistic
Arena

- 60 x 65 cm² arena
- 25 blades
- With and without absolute localization
- Faithfully reproduced in Webots
Performance Estimation

• Circumnavigation of a blades boundary
  – No “inspection”
• Monitor progress using overhead vision
• Analysis using SwisTrack
  http://swistrack.sourceforge.net
Robotic Platform

- **Basis:** Miniature Robot *Alice II*  
  (Caprari & Siegwart, 2005)

- 2cm x 2cm x 2cm
- PIC MCU at 4MHz
- 368 Byte RAM
- 4 infra-red distance sensors (3cm)
- Local communication (6cm)
- 4cm/s max. speed
Communication Module

- Compatible to Telos Mote IV
  (Polastre, Szewczyk & Culler 2005)

- I²C Support
  (Cianci, Raemy, Pugh & Martinoli 2006)

- TI MCU at 8MHz

- 4KByte RAM

- 2.4GHz radio (802.15.4)
Camera Module

- Down-sampled VGA camera
- PIC MCU
- 16MHz
- 4KByte RAM
- Color-bar encoding algorithm
Distributed Boundary Coverage Algorithms
Different Coordination Schemes for Multi-Robot Systems

- Deliberative
- Reactive
- Simple nodes
- Complex nodes
- No Comm.
- Communication

Degree of deliberation vs. Degree of coordination

A Suite of 5 Algorithms

• 2 fully reactive algorithms:
  – Without explicit collaboration and absolute localization
  – With collaboration (blade marking) but without absolute localization

• 3 deliberative algorithms:
  – Planning without absolute localization, no collaboration
  – Planning with absolute localization and collaboration (blade map sharing)
  – Planning with absolute localization and collaboration (blade market)
Reactive Algorithms: No Planning
Reactive Algorithms for Distributed Boundary Coverage

1. Algorithms for extremely simple, miniature robots
2. **Analyze and synthesize** distributed control using probabilistic population dynamic models

Local communication, limited computation, no absolute localization
Reactive Coverage without Collaboration and Abs. Localization

Search

Inspect

Translate

Avoid Obstacle

Search

Inspect

Translate along blade

Wall | Robot

Obstacle clear

Blade

$1-p_t$

$T_t$ expired

$p_t$

Planning

Coordination
Real Robot Video
Corresponding Probabilistic Model

Robotic System

Environment
Parameter Calibration

- Encountering probability
  - Detection area
  - Robot speed
  - Sensor range
- Interaction times
  - Dedicated experiments
  - Geometry
- Improvement by data-fitting (constrained system identification technique)

[Correll & Martinoli, DARS 2006]
Model Prediction vs. Real Robot Experiments

20 robots  25 robots  30 robots

[Correll & Martinoli, DARS 2006]
Deliberative Algorithms: Planning
Deliberative Algorithms for Distributed Boundary Coverage

- Deliberative planning
  - Creating a map of the environment
  - Moving towards unexplored areas
- Incrementally raising capabilities of robotic platform
Deliberative Boundary Coverage
without Absolute Localization and Explicit Collaboration

- Build a minimal spanning-tree on-line
- Move from blade to blade reactively
- Localization by counting blades
- Start-over when lost
Deliberative Algorithms for Distributed Boundary Coverage

• Efficient localization needed for effective exchange of information

• Known maps: near-optimal allocations
Deliberative Coverage with Absolute Localization and Explicit Collaboration

- Build a minimal spanning-tree on-line
- Move from blade to blade reactively
- Absolute localization using camera
- Share progress using explicit communication
Robustness

• Sources of error:
  – navigation error $\pi_e$
  – localization error $p_f$
  – blade attachment

• Algorithm plans always using its current location

• Communication + localization failure leads to performances similar to the first deliberative algorithm

• Patrolling
Real Robot Video

[Rutishauer et al., *Robotics and Autonomous Systems*, 2009]
Market-Based Coordination

- Robots calculate cost for covering a blade by solving the TSP
- Sequential bidding yields near-optimal allocation
- Deterministic bid evaluation allows for decentralized auction-closing
- Re-allocation upon error
Real Robot Video

Comparing all the Five Algorithms
Quantitative Performance Comparison

- **RC**: reactive, implicit collaboration
- **RCMM**: reactive, explicit collaboration using robot as blade markers (beacons)
- **DCWL**: deliberative, implicit collaboration, without absolute localization
- **DCL/MCR**: deliberative, collaborative with localization (DCL: map sharing; MCR: task trading)

[Correll and Martinoli, *IEEE RAM*, 2009]
Conclusion
Take Home Messages

- Target localization (e.g., victims, chemical sources, anti-personnel mines, sound sources), coverage, mapping, inspection, and environmental monitoring are concrete applications for robotic sensor networks.
- All media and physical domains: 2D, 3D, water, ground, air.
- Sensing payload and robotic platform very specific to the application.
- Node control is data-aware: often close-loop control of mobility based on field data gathered.
- Multiple algorithms for solving the same distributed sensing mission, from reactive to deliberative.
- Multi-robot coordination: loose or tight; depends often on the localization and networking capabilities of the robots in the specific environment.
Additional Literature – Week 13 and 14


Course Conclusion
Take Home Messages

• Distributed Intelligent Systems (DISs) show natural and artificial (virtual or real) forms

• Artificial and natural DISs differ quite a bit in their physical substrate and algorithms/design solutions proposed for natural systems can often be applied in a straightforward way in virtual scenarios but with more care in the real world

• Various classes of algorithms, model-based and data-driven (machine-learning) methods have been presented in the course for the coordination, analysis and synthesis of DISs
Take Home Messages

• Local interaction mechanisms ensure system scalability; individual simplicity often implies additional robustness at the cost of a reduced efficiency

• Swarm Intelligence is one form of distributed intelligence relying on self-organization as coordination mechanism; it often also leverages stigmergy as indirect communication mechanism; it targets systems consisting of a large number of simple units

• Distributed intelligence strategies can be applied to wireless sensor networks but performance in reality is often dominated by other factors and design choices, minimizing the impact of such strategies
Take Home Messages

• Further local capabilities (e.g., additional computation resources, explicit communication, and localization) can be used to enhance the collective performance

• Further coordination mechanisms exploiting longer range, explicit communication, and points of centralization can be competitive at the cost of a higher node complexity or reduced mobility

• Volume/mass/cost of single nodes determine available energy, S&A accuracy, communication, computation, and mobility capabilities, etc. and software/hardware choices must be well matched to obtain competitive systems
The end:
Thanks for your attention over the whole course!