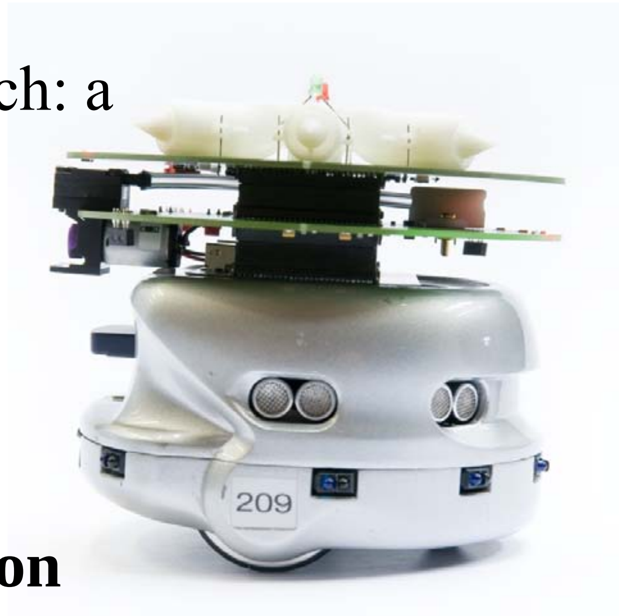
ÉCOLE POLYTECHNIQUE
FÉDÉRALE DE LAUSANNE

Distributed Intelligent Systems – W13 and W14:

Distributed Sensing using Robotic Sensor Networks

Outline

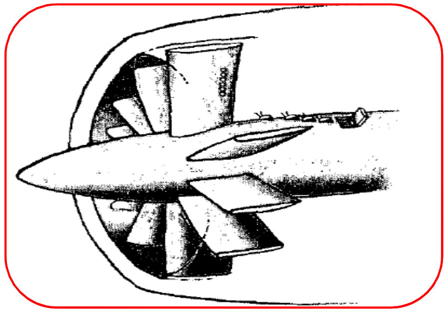
- Robotic sensor networks: challenges and applications
- Robotic sensor networks for distributed search: a case study on odor source localization
  – Challenges and approach
  – Single robot algorithms
  – Multi-robot algorithms
- **Robotic sensor networks for distributed coverage: a case study on turbine inspection**
  – **Challenges and approach**
  – **Reactive distributed algorithms**
  – **Deliberative distributed algorithms**



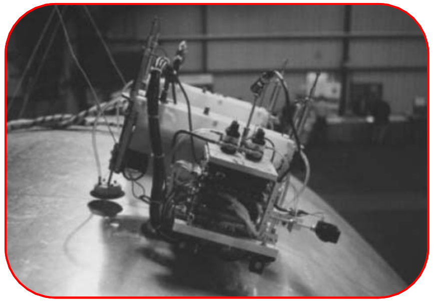
Robotic Sensor Networks for Turbine Inspection

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



© Litt, NASA Glenn, 2003

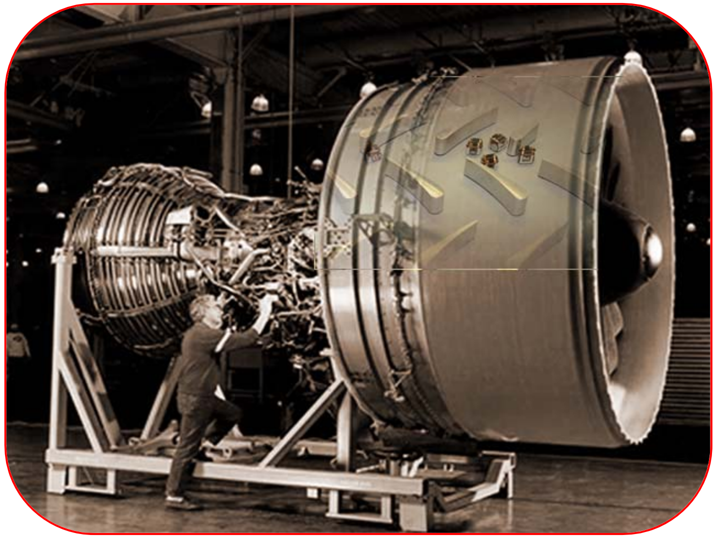


© Siegel & Gunatilake 1997

© Tache, Mondada, Siegwart et al. 2007

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

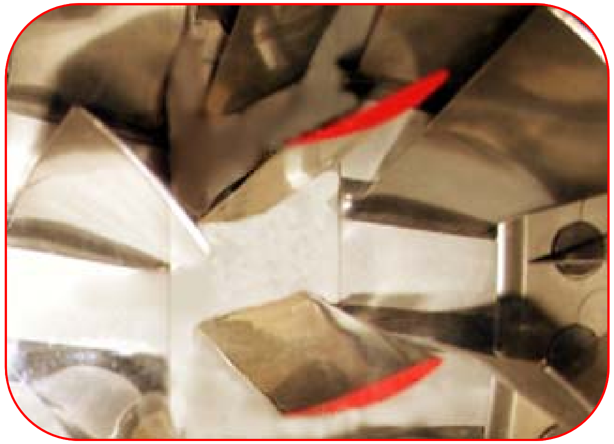


[Correll, PhD thesis, 2007]

Miniaturization

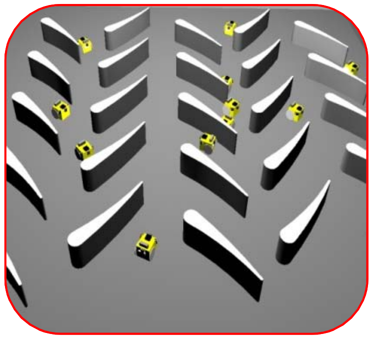
- Size constraints render single robot approach infeasible
- Miniaturization implies constraints on
  - Energy
  - Computation
  - Sensor and actuator accuracy
  - Communication

System behavior essentially probabilistic



Arena

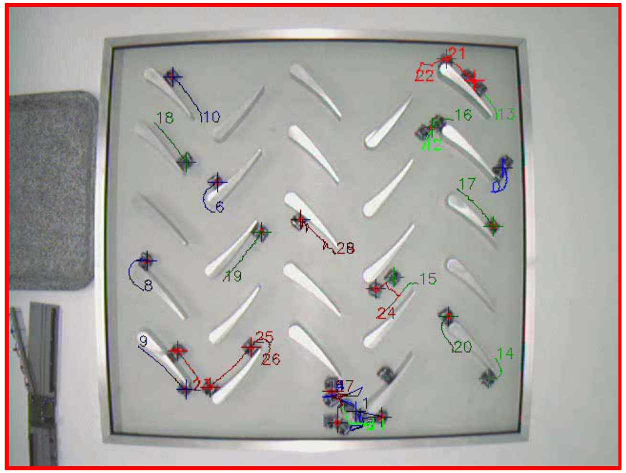
- 60 x 65 cm^2 arena
- 25 blades
- With and without absolute localization
- Faithfully reproduced in Webots



ÉCOLE POLYTECHNIQUE
FÉDÉRALE DE LAUSANNE

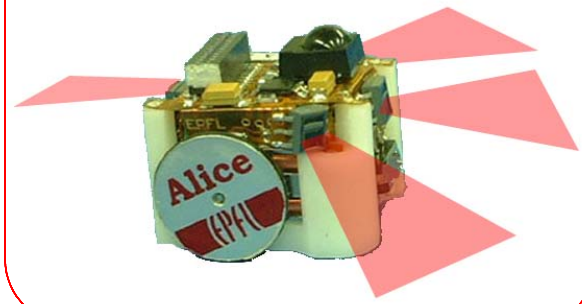
Performance Estimation

- 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)

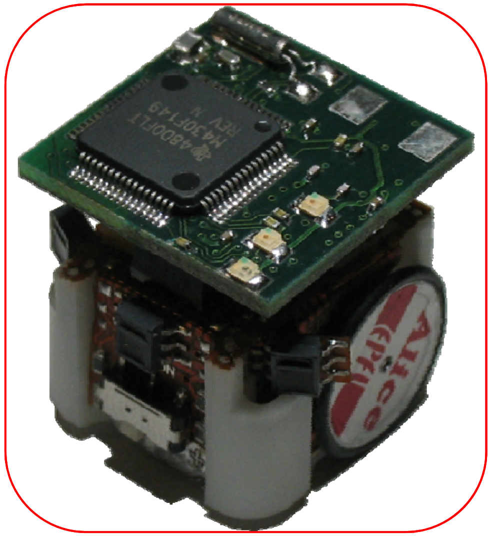


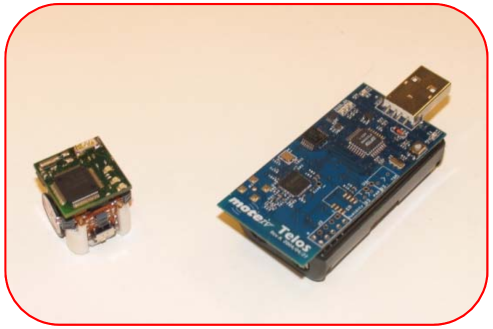
- 2cm x 2cm x 2cm
- PIC MCU at 4MHz
- 368 Byte RAM
- 4 infra-red distance sensors (3cm)
- Local communication (6cm)
- 4cm/s max. speed

ÉCOLE POLYTECHNIQUE
FÉDÉRALE DE LAUSANNE

Communication Module

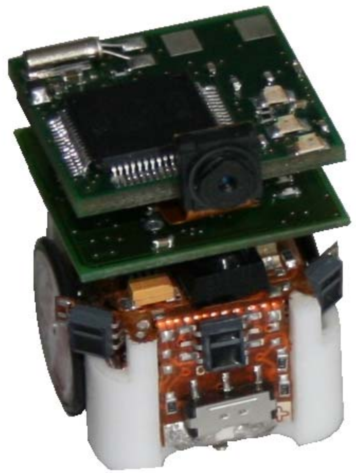
- Compatible to Telos Mote IV
  (Polastre, Szewczyk & Culler 2005)
- I^{2}C Support
  (Cianci, Raemy, Pugh & Martinoli 2006)
- TI MCU at 8MHz
- 4KByte RAM
- 2.4GHz radio (802.15.4)





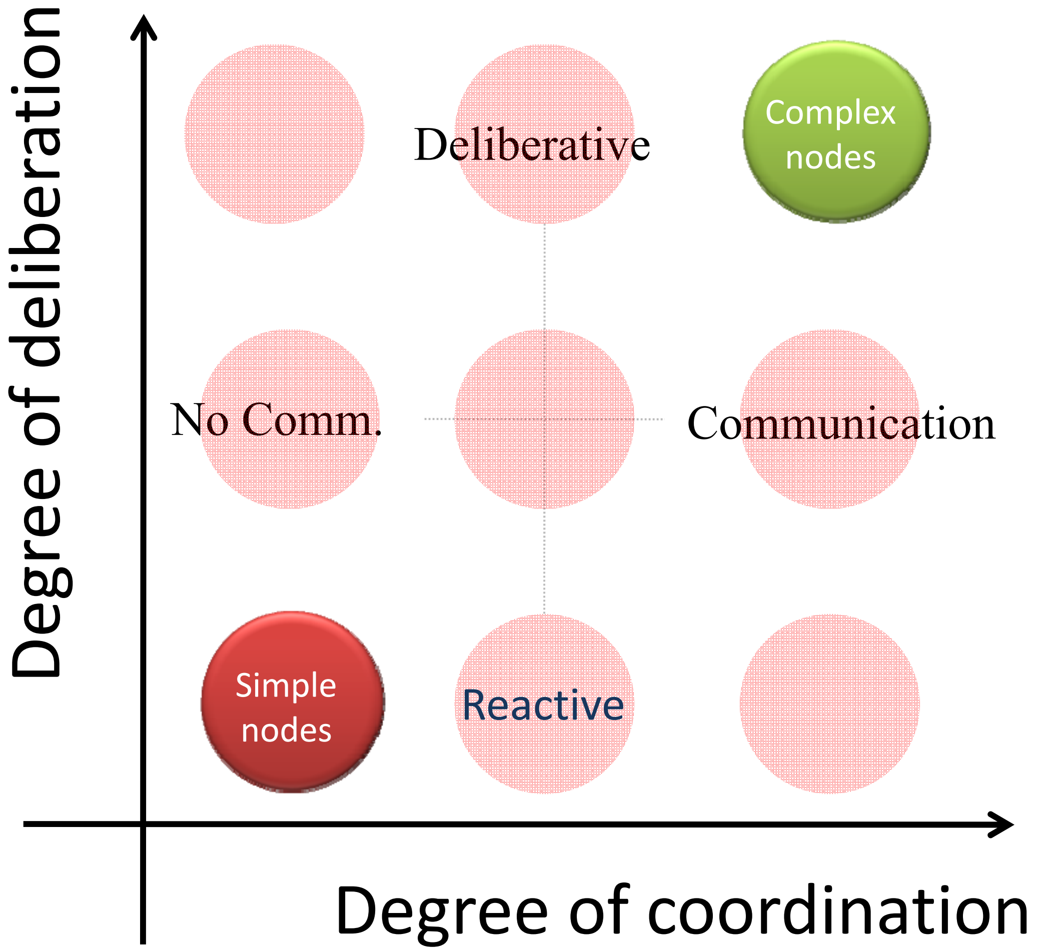
Camera Module

- Down-sampled VGA camera
- PIC MCU
- 16MHz
- 4KByte RAM
- Color-bar encoding algorithm



Distributed Boundary Coverage Algorithms

Different Coordination Schemes for Multi-Robot Systems



[Kalra, PhD Thesis, CMU 2006]

A Suite of 5 Algorithms

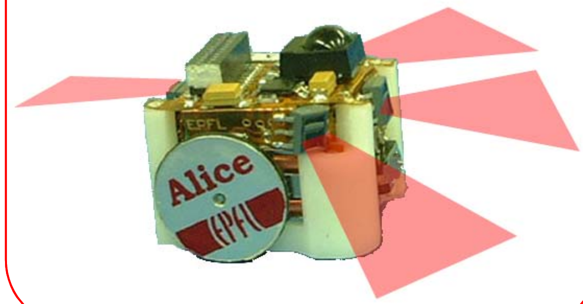
- 2 fully reactive algorithms:
  - Without explicit collaboration and absolute localization
  - With collaboration (blade marking) but without absolute localization
- 3 deliberative algorithms:
  - Planning without absolute localization, no collaboration
  - Planning with absolute localization and collaboration (blade map sharing)
  - Planning with absolute localization and collaboration (blade market)

ÉCOLE POLYTECHNIQUE
FÉDÉRALE DE LAUSANNE

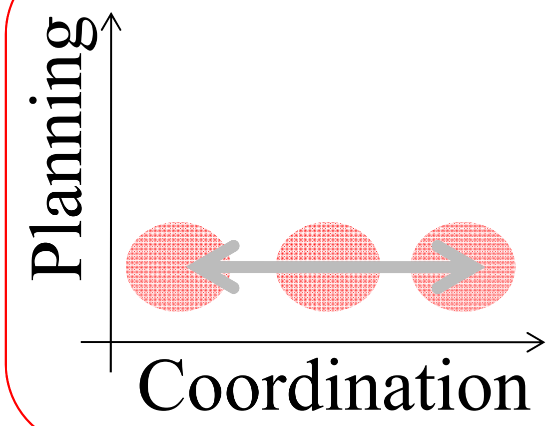
Reactive Algorithms: No Planning

Reactive Algorithms for Distributed Boundary Coverage

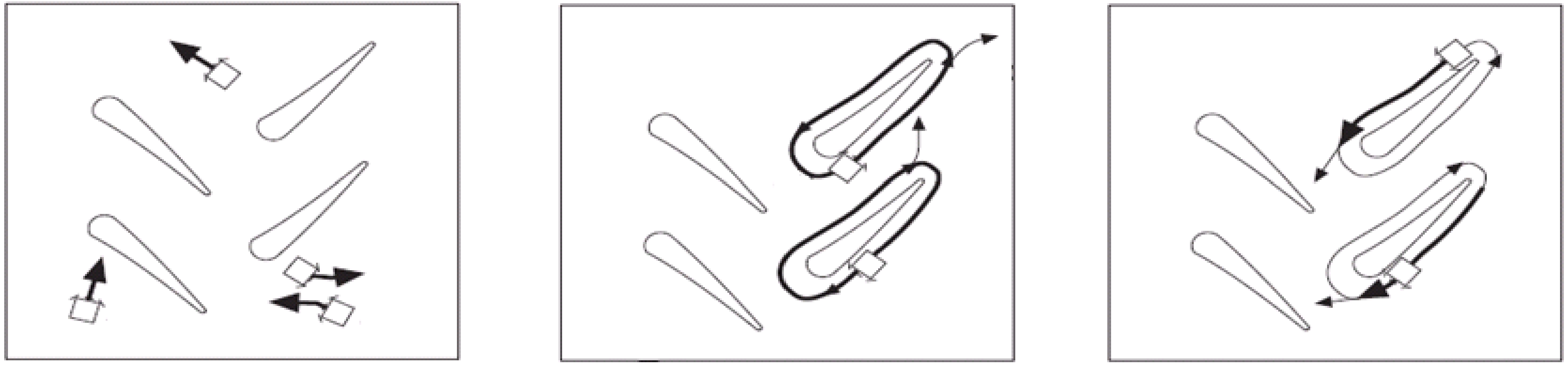
1. Algorithms for extremely simple, miniature robots
2. Analyze and synthesize distributed control using probabilistic population dynamic models



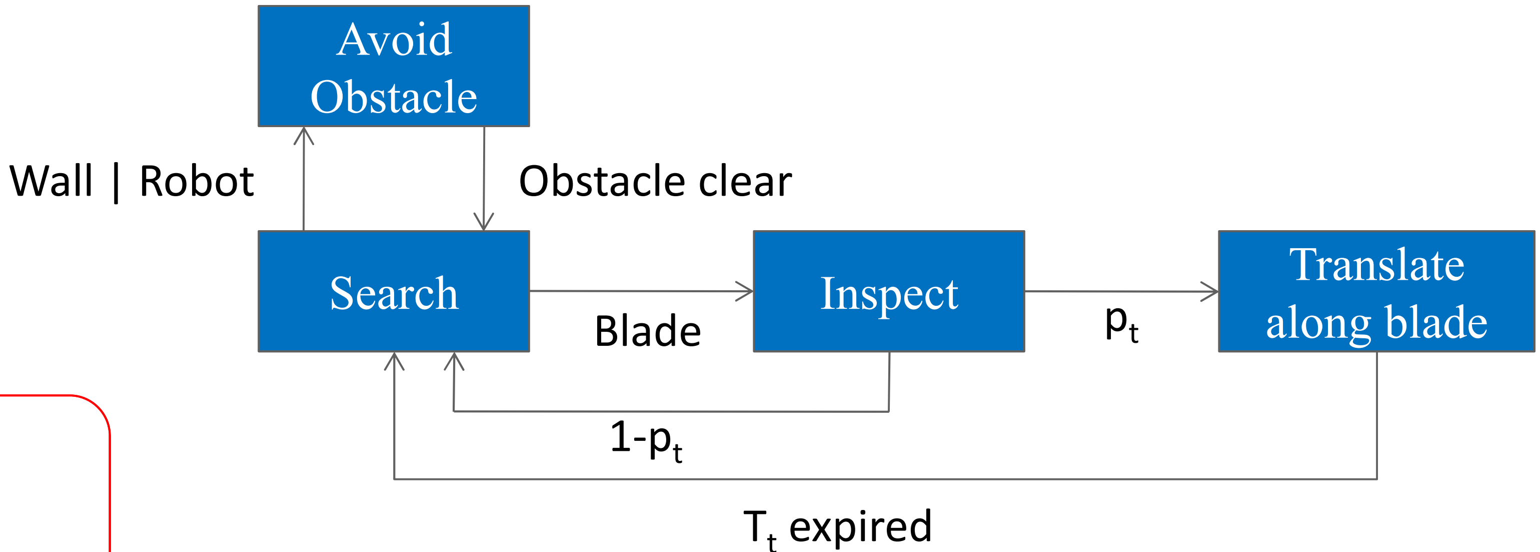
Local communication, limited computation, no absolute localization

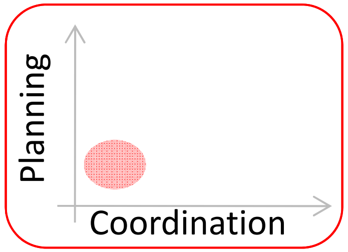


Reactive Coverage without Collaboration and Abs. Localization

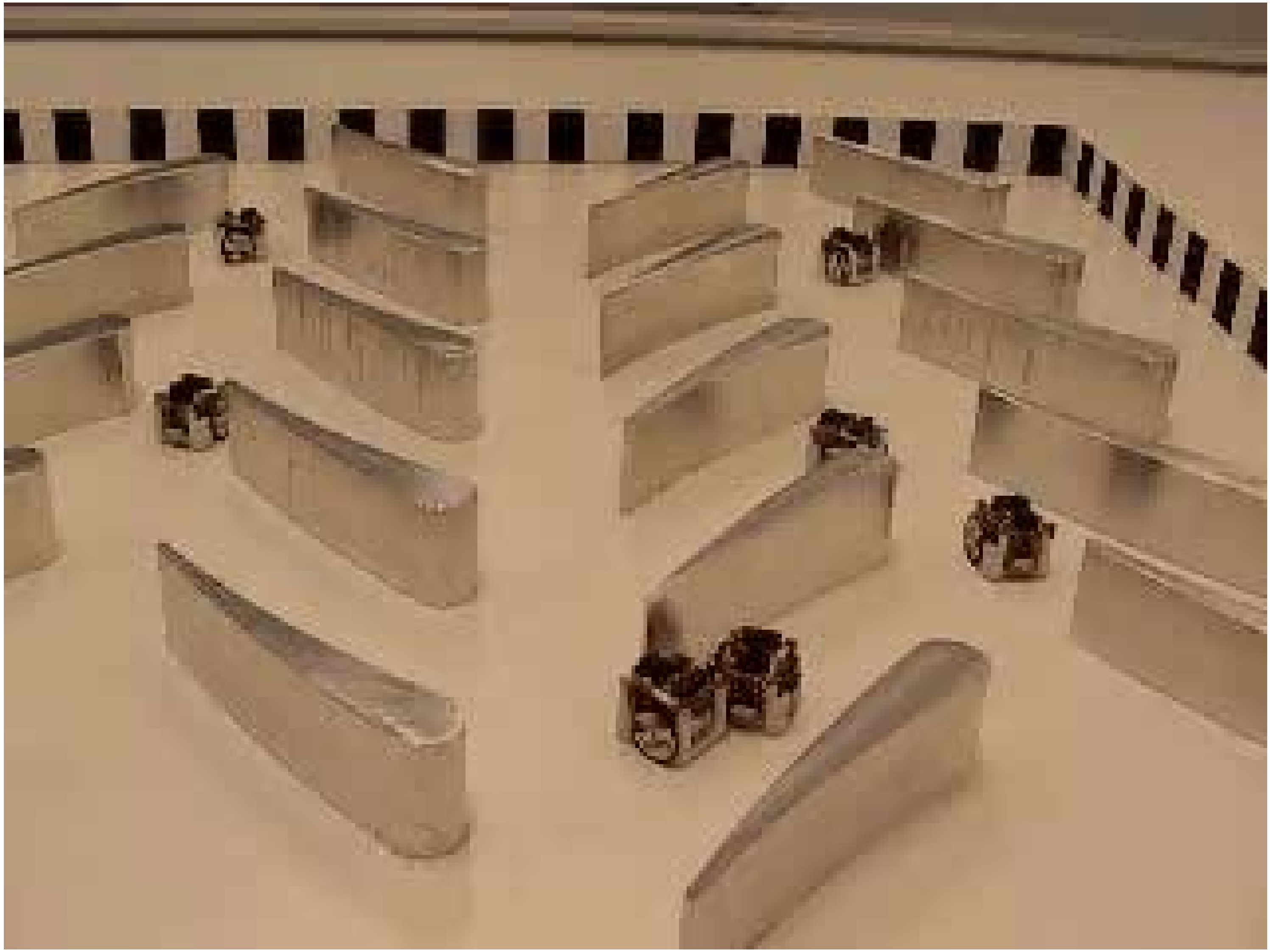


Search Inspect Translate

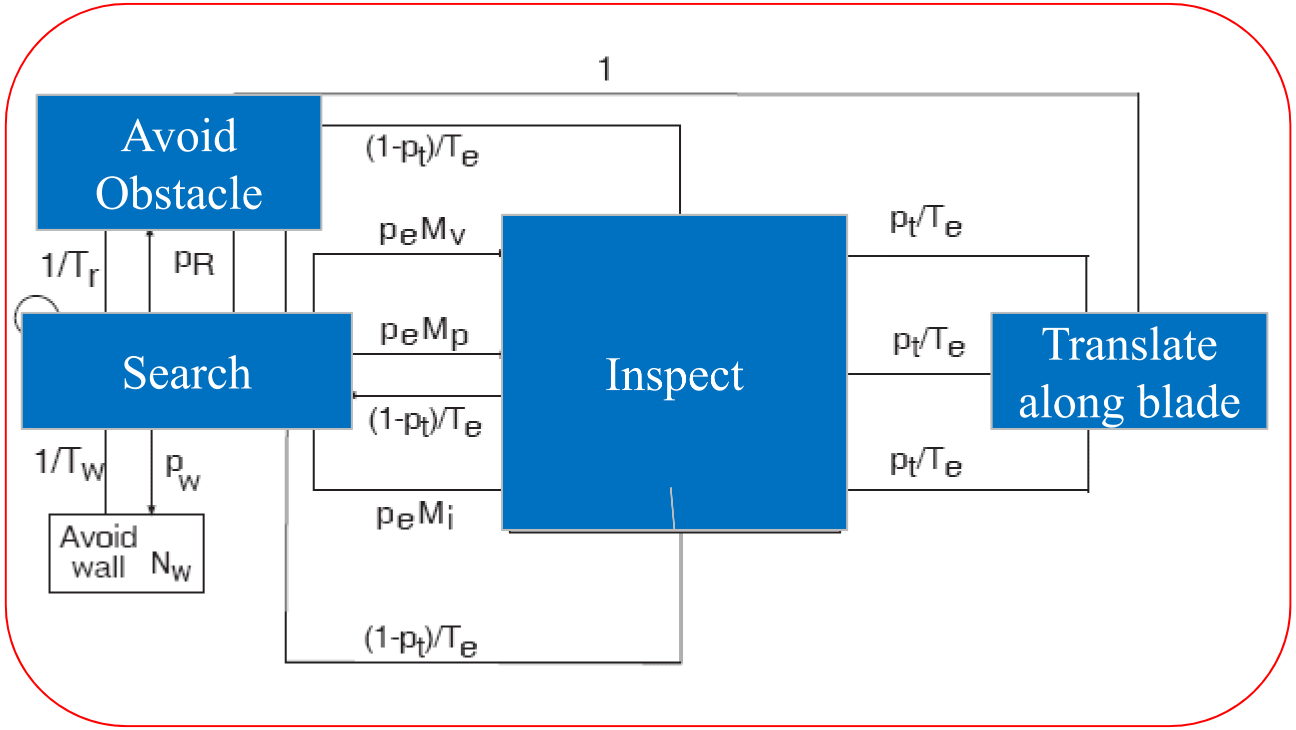




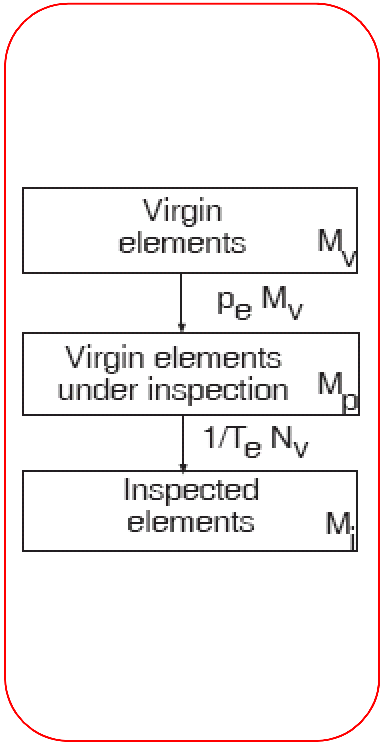
Real Robot Video



Corresponding Probabilistic Model



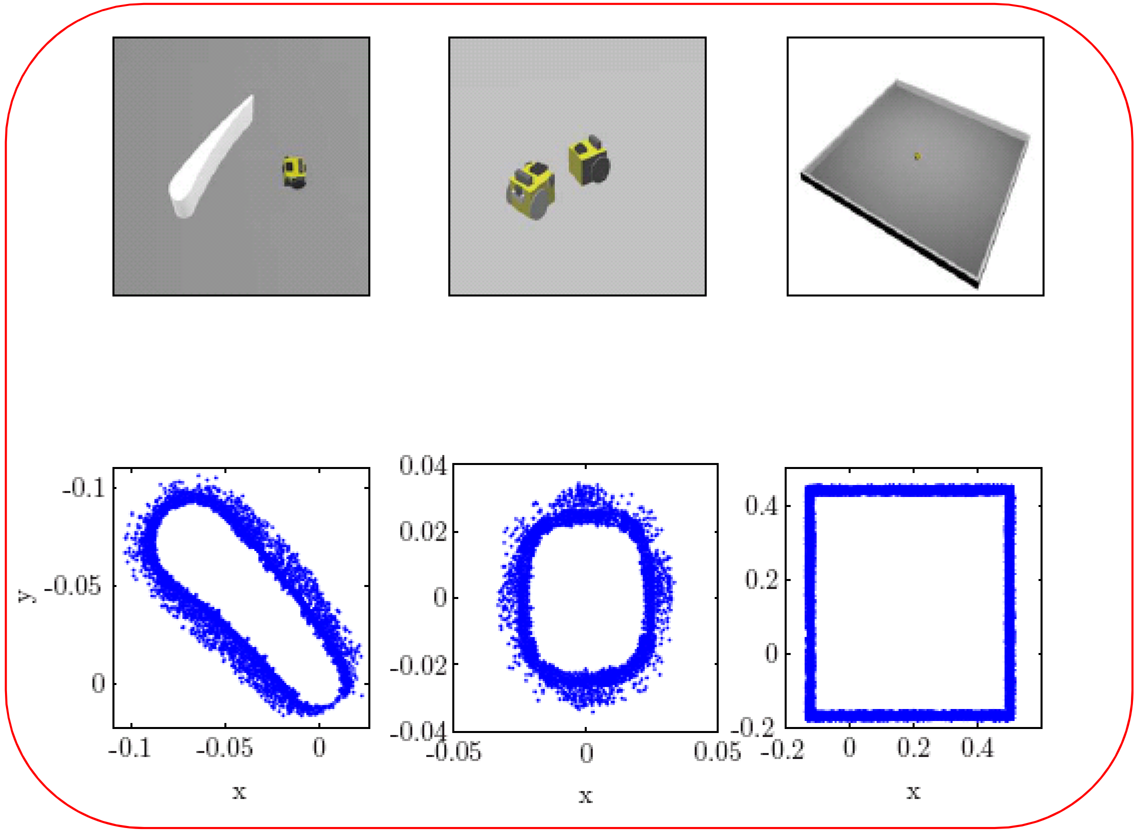
Robotic System



Environment

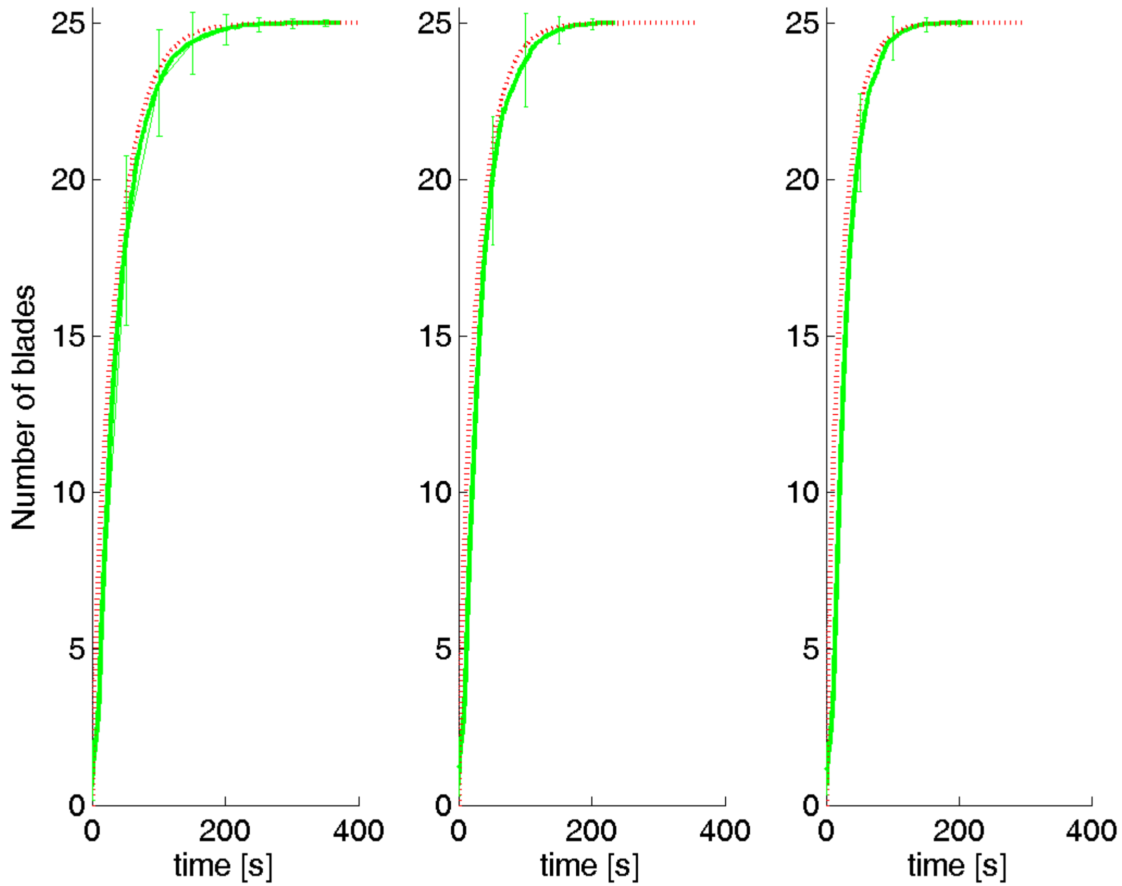
Parameter Calibration

- 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



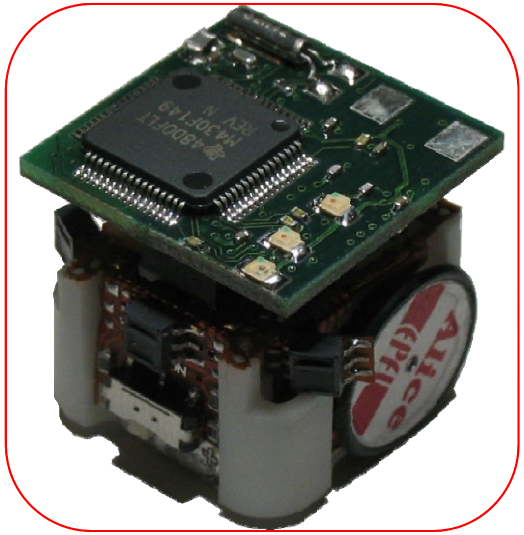
20 robots 25 robots 30 robots

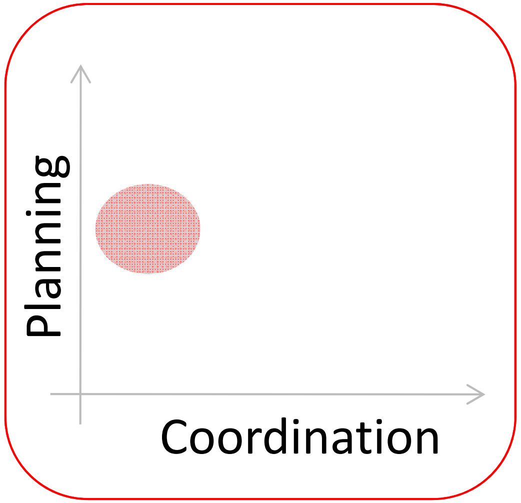
[Correll & Martinoli, DARS 2006]

Deliberative Algorithms: Planning

Deliberative Algorithms for Distributed Boundary Coverage

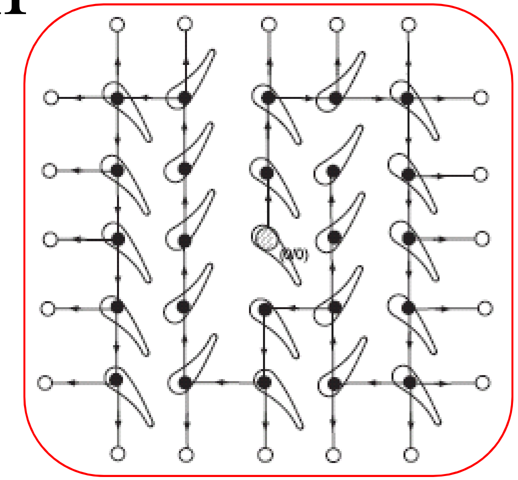
- Deliberative planning
  - Creating a map of the environment
  - Moving towards unexplored areas
- Incrementally raising capabilities of robotic platform

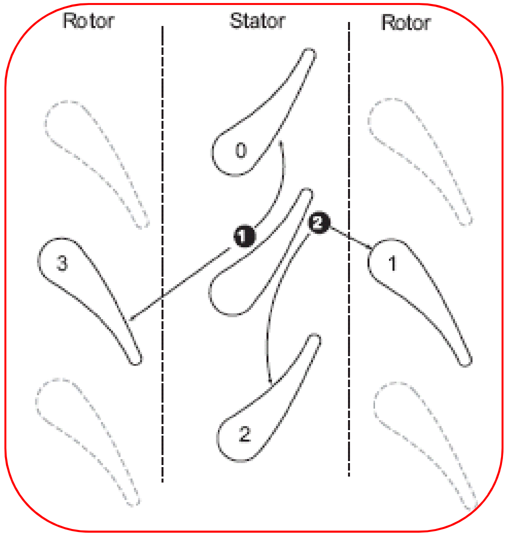




Deliberative Boundary Coverage without Absolute Localization and Explicit Collaboration

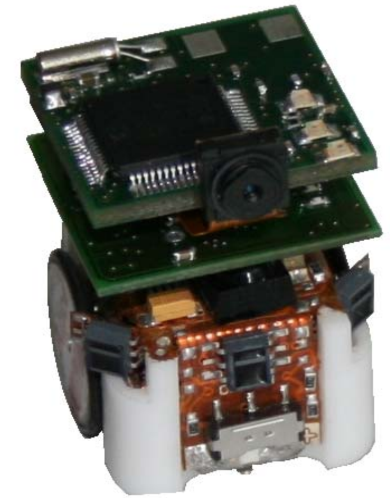
- Build a minimal spanning-tree on-line
- Move from blade to blade reactively
- Localization by counting blades
- Start-over when lost

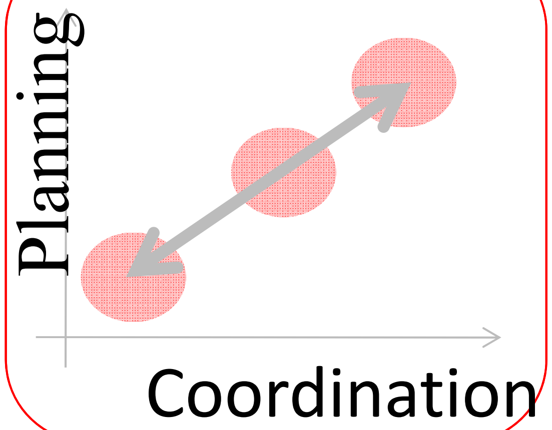




Deliberative Algorithms for Distributed Boundary Coverage

- Efficient localization needed for effective exchange of information
- Known maps: near-optimal allocations

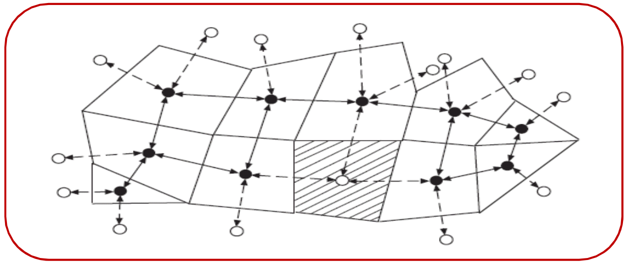




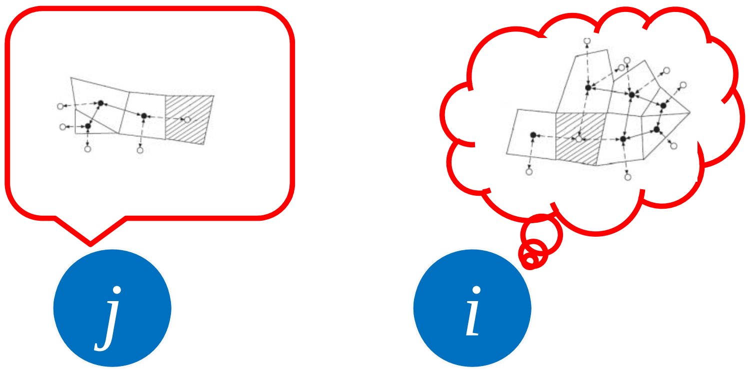
ÉCOLE POLYTECHNIQUE
FÉDÉRALE DE LAUSANNE

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



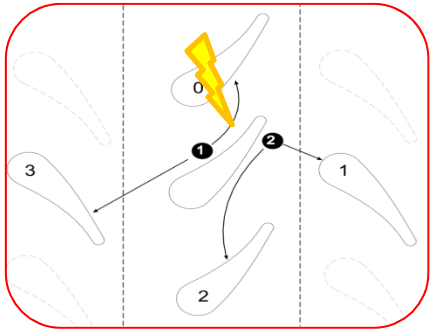
$$G = (\mathcal{V}, \mathcal{E})$$

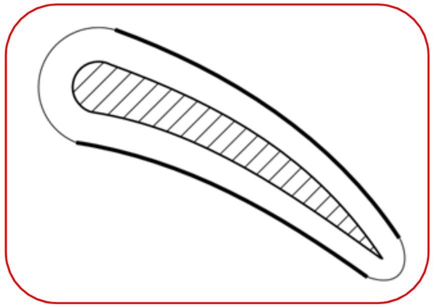


$$G^i_{t+\epsilon} = G^i_t \cup G^j_t$$

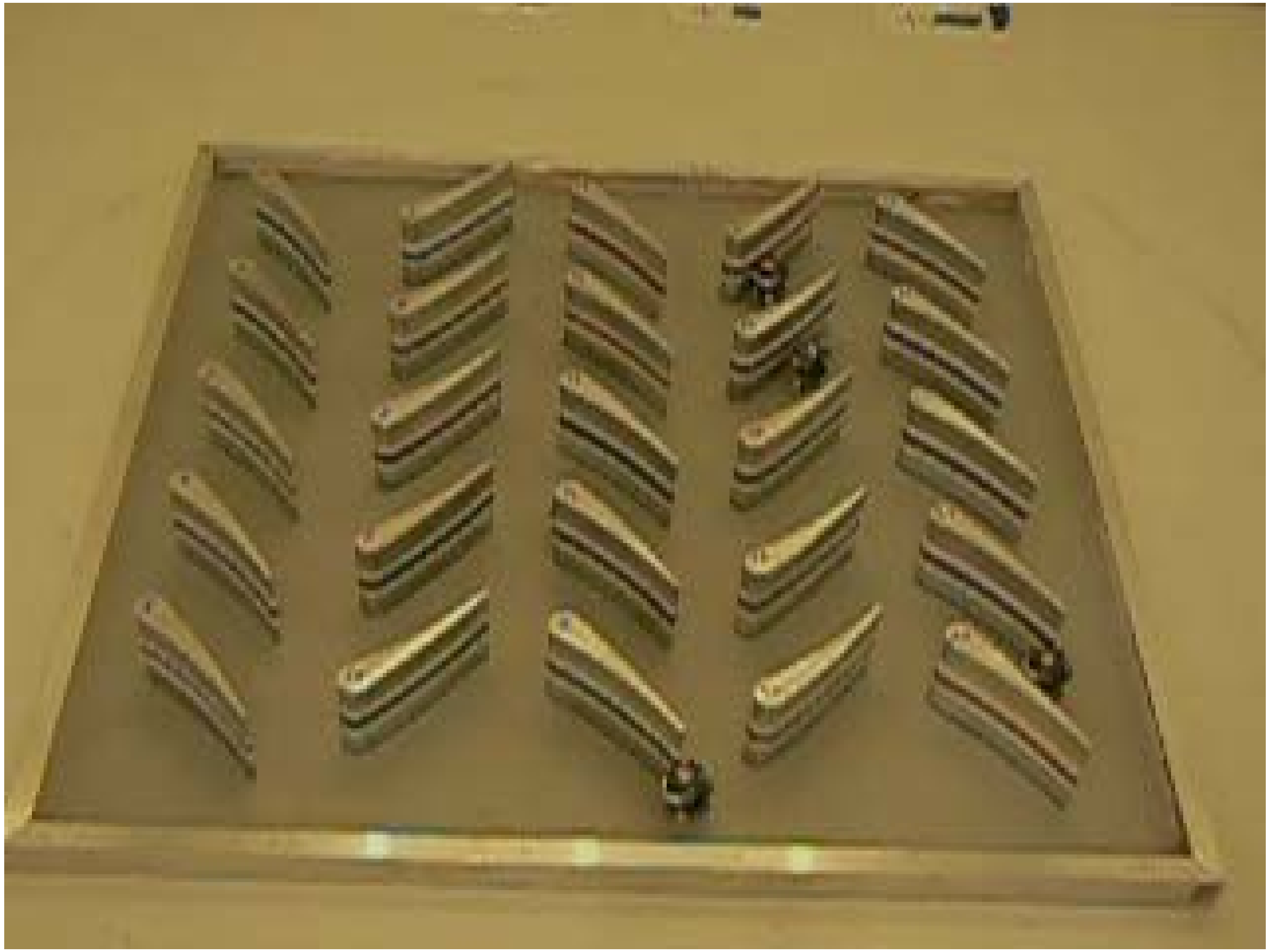
Robustness

- Sources of error:
  - navigation error π_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





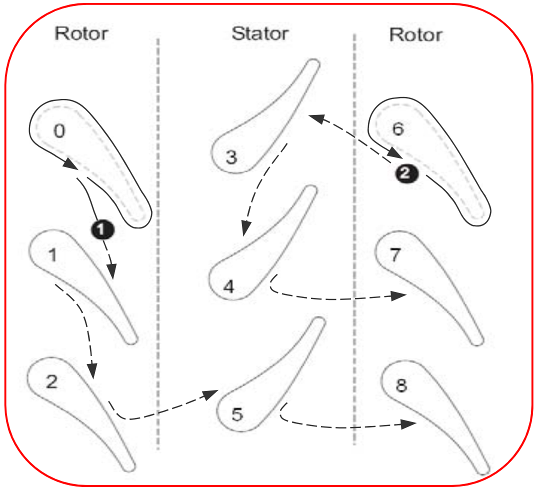
Real Robot Video

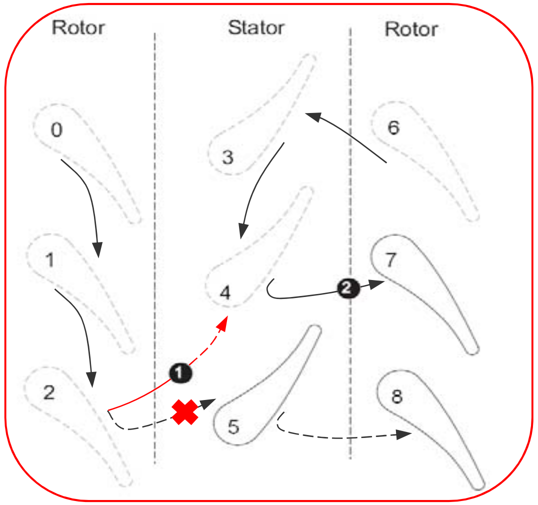


[Rutishauser et al., *Robotics and Autonomous Systems* , 2009]

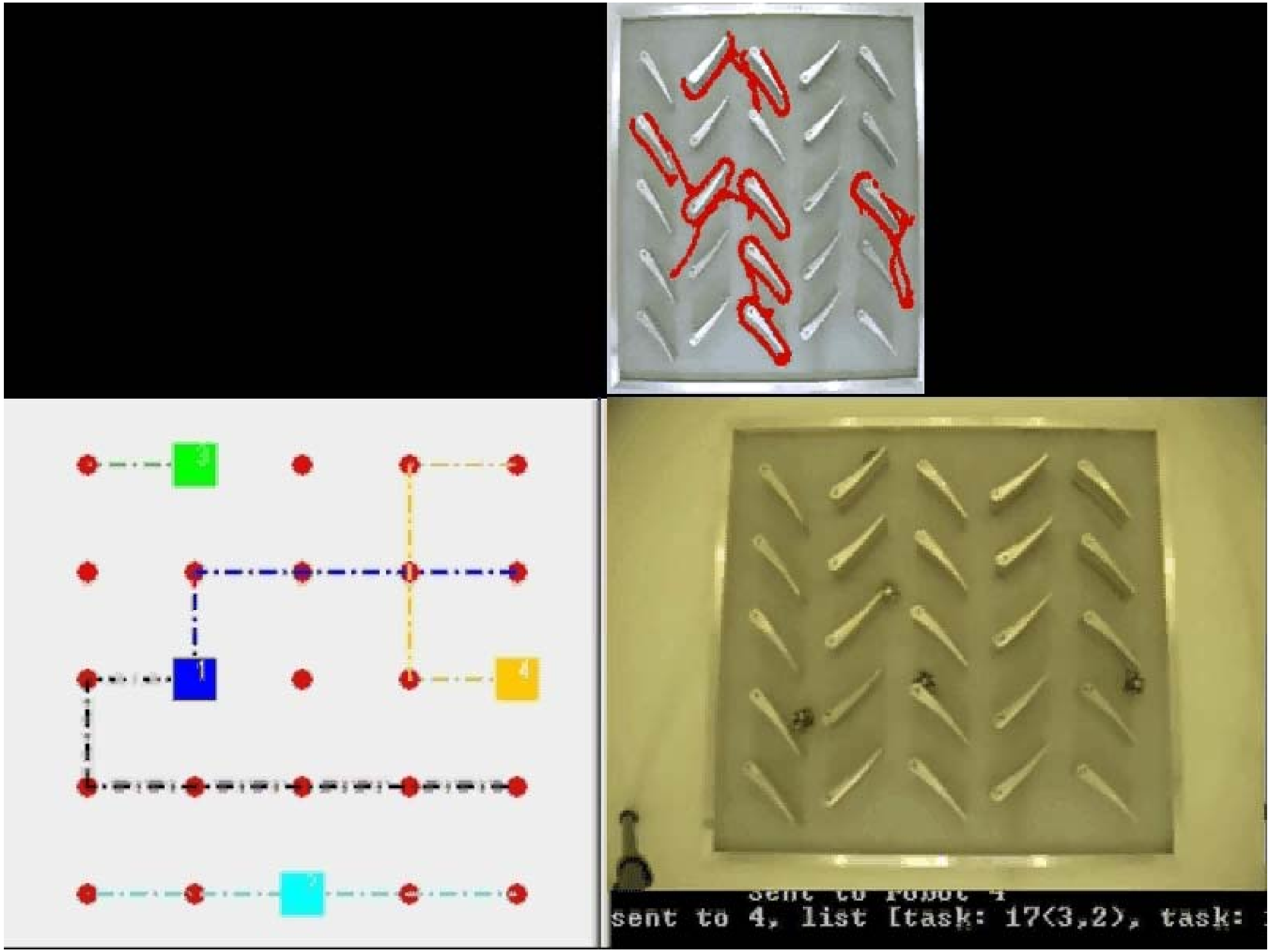
Market-Based Coordination

- 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

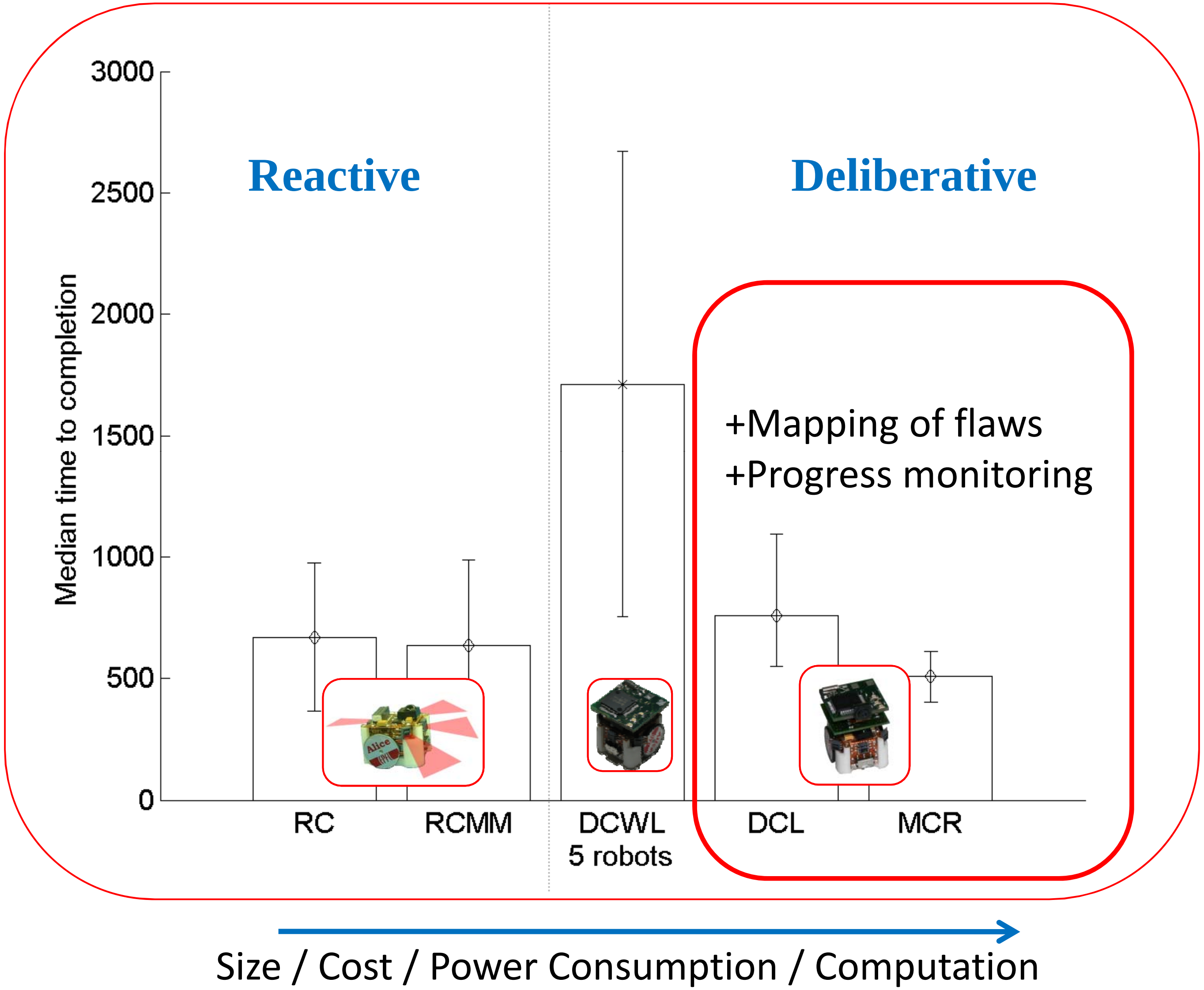


[Amstutz et al., *Annals of Mathematics and Artificial Intelligence*, 2009]

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

ÉCOLE POLYTECHNIQUE
FÉDÉRALE DE LAUSANNE

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.

ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

Additional Literature – Week 13 and 14

- Lochmatter T., Raemy X., Matthey L., Indra S. and Martinoli A., "A Comparison of Casting and Spiraling Algorithms for Odor Source Localization in Laminar Flow". *Proc. of the 2008 IEEE Int. Conf. on Robotics and Automation*, May 2008, Pasadena, U.S.A., pp. 1138 – 1143.
- Lochmatter T. and Martinoli A., "Theoretical Analysis of Three Bio-Inspired Plume Tracking Algorithms". *Proc. of the 2009 IEEE Int. Conf. on Robotics and Automation*, May 2009, Kobe, Japan, pp. 2661-2668.
- Soares J. M., Marjovi A., Giezendanner J., Kodiyan A., Aguiar A. P., Pascoal A. M., and Martinoli A., "Towards 3-D Distributed Odor Source Localization: An Extended Graph-Based Formation Control Algorithm for Plume Tracking," *Proc. of the IEEE/RSJ Int. Conf. on Intelligent Robots and Systems,* October 2016, Daejeon, Korea, pp. 1729-1736.
- Rahbar F., Marjovi A., Kibleur P., and Martinoli A., "A 3-D Bio-inspired Odor Source Localization and its Validation in Realistic Environmental Conditions," *Proc. of the IEEE/RSJ Int. Conf. on Intelligent Robots and Systems*, September 2017, Vancouver, Canada, pp. 3983–3989.
- G. Caprari, A. Breitenmoser, W. Fischer, C. Hürzeler, F. Tâche, R. Siegwart, O. Nguyen, R. Moser, P. Schoeneich and F. Mondada, "Highly Compact Robots for Inspection of Power Plants", *Journal of Field Robotics*, vol. 29, no. 1, pp. 47–68, 2012.
- A. Breitenmoser, J. Metzger, R. Siegwart and D. Rus, "Distributed Coverage Control on Surfaces in 3D Space", In *Proc. of the IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, pp. 5569–5576, Taipei, Taiwan, October 2010.
- A. Breitenmoser, F. Tâche, G. Caprari, R. Siegwart and R. Moser, "MagneBike—Toward Multi Climbing Robots for Power Plant Inspection", In *Proc. of the 9th International Conference on Autonomous Agents and Multiagent Systems (AAMAS)*, pp. 1713–1720, Toronto, Canada, May 2010.

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

ÉCOLE POLYTECHNIQUE
FÉDÉRALE DE LAUSANNE

The end:
Thanks for your attention over the whole course!