When Opportunity Proceeds from Autonomy:

A Tour-Based Architecture for Disconnected Mobile Sensors

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Sensing agents with **autonomous mobility** work **cooperatively** towards a **mission** in a **vast** and **challenging** environment.

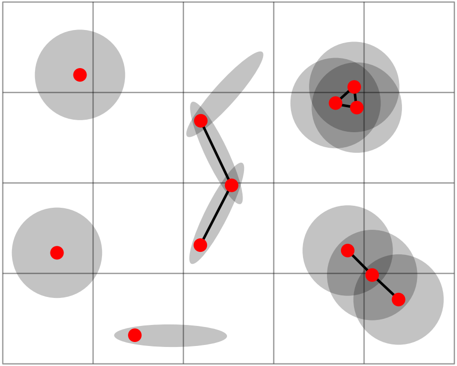
Illustration:

Solar-powered Autonomous Underwater Vehicles (SAUVs) using acoustic communication

Assumptions:

- agents need to communicate in order to cooperate;
- environmental challenges hinder or prevent long-range communication;
- agents need to move (e.g., towards each other) to communicate;
- agents need to move (possibly away from each other) to sense;
- agents may break down in a variety of ways.

Motion, Communication, Mission



- **communication** enabled by **motion**, and **autonomous motion** driven by a **mission**;
- **impossibility** (vastness, communication ranges) or **undesirability** (stealth missions, low-power devices) to maintain **global network**;
- standard **networking** apparatus available only to **groups** of agents.

Two Key Problems

Disconnected agents:

no global network, even with multi-hops and high latency:

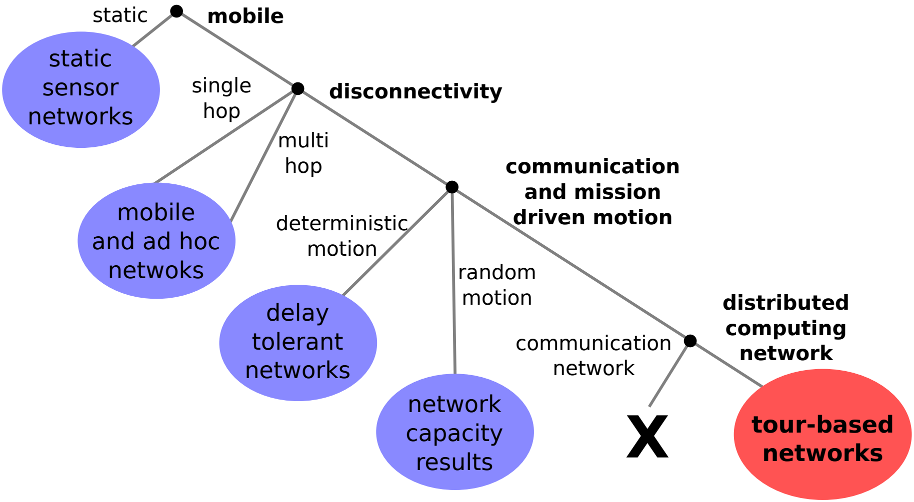
- agents form groups and interact locally, given the opportunity;
- mission implementations are designed in terms of these groups (instead of a more standard address-based, packet-routing abstraction)

Complex motion design:

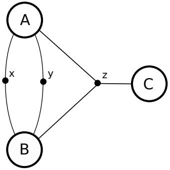
motion used for individual tasks **and** for communication:

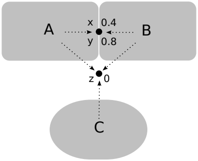
- low-level motion primitives result in complex or fragile designs;
- instead, sensing, motion and communication are combined into new high-level building blocks;
- robust implementation of these building blocks is achieved through a supporting architecture.

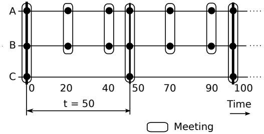
→ **tour**-based **architecture**


static
mobile
static sensor networks
single hop
disconnectivity
multi hop
mobile and ad hoc netwoks
communication and mission driven motion
deterministic motion
random motion
delay tolerant networks
distributed computing network
communication network
network capacity results
X
tour-based networks

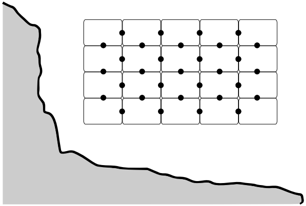
Tours, Meeting Points and Tour Networks

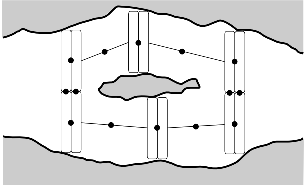




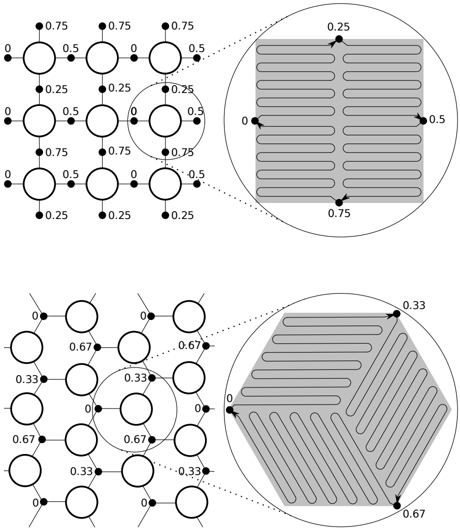


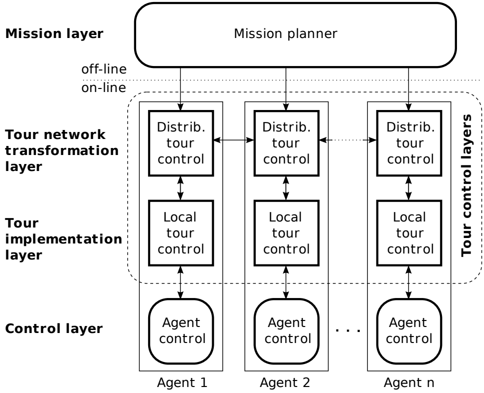
- agents are in charge of **tours**:
  - an area to scan
  - a collection fo **meeting points**
  - a periodic schedule of meetings
- tours are assembled into **tour networks** to implement missions in which agents only interact at meeting points



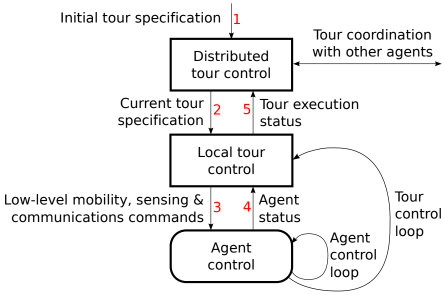


- an individual agent **trajectory** travels the tour area while visiting meeting points according to the schedule
- **groups** of agents form at meeting points to perform **joint operations** designed in accordance to the mission
- trajectories are implemented using low-level **motion primitives**
- joint operations are implemented using existing techniques from **ad-hoc** networking and **distributed computing**

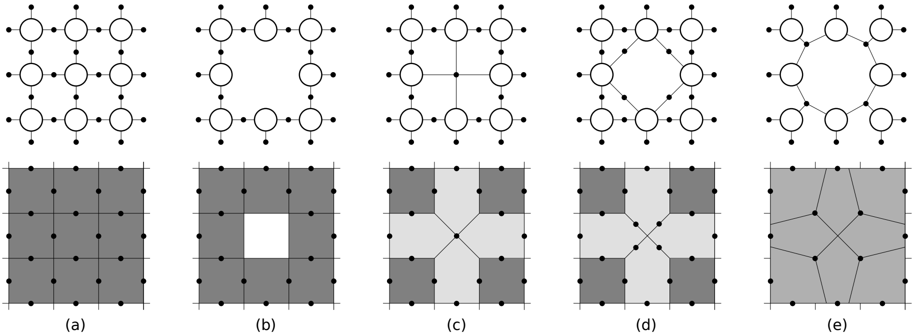




- **Mission** layer: initial, stable-state, tour-based design
- **Tour network transformation** layer: tour network reconfiguration (adaptation, repair), may involve coordination among agents
- **Tour implementation** layer: current tour execution (design and follow a suitable trajectory, attend meetings)
- **Control** layer: low-level implementation of motion, sensing and communication involved in a trajectory and its meetings



1. tour-based **design** and its desirable **properties** (to be maintained by transformations), ...
2. tour **area** to monitor, **meeting points** to travel to, **schedule** of meetings, **computation steps** to perform, ...
3. **motion** commands to follow current trajectory, **communication** commands to interact at meetings, **sensing** commands, ...
4. current **motion**, **communication** and **sensing** capabilities, data on **environment** (e.g., presence of other agents), ...
5. **status** of last meetings (e.g., missing agents), expected **delays**, **requests** for tour modifications, ...



- **transformations** are triggered by **failures**, the need to **adapt** to environmental changes, or other transformations;
- they impact tour network **topology** and **geometry**;
- hence, they impact **scanning rates** and **information propagation**;
- they involve tradeoffs between **optimality** and **locality**.

Tour-network metrics:

Problem: different transformations offer different benefits

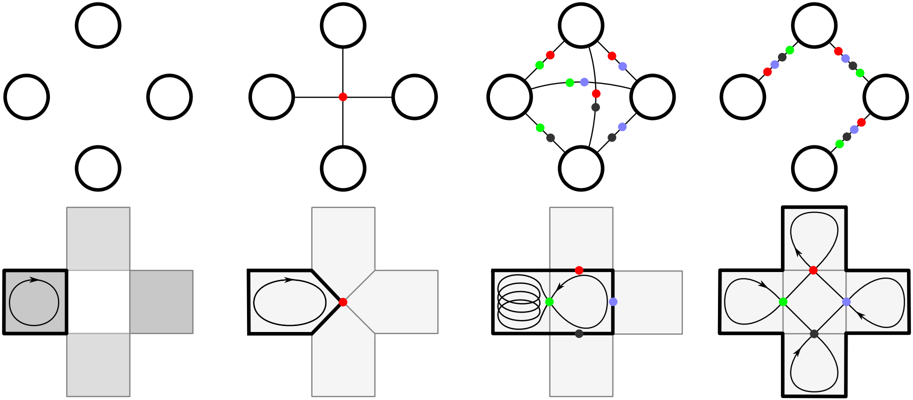
- **scanning rates:** minimum, average, gaps without visits, ...
- **information propagation:** agent to agent, one to many, from inside to the edges, from the edges, ...
- **meeting size:** min, max, ...
- **trajectory:** length, complexity of schedules, number of meetings, areas visited/ignored, ...
- **robustness:** resilience to further failures and changes, availability of further transformations, ...

Implementation:

Problem: transformations need be implemented locally and reliably

- **joint** decision at meetings or **distributed consensus** from several independent meetings
- agents must maintain **approximations** of the **states** of other agents for certain **neighborhoods**
- recovery from **failed** transformations

Tour-Network Transformations: Examples



- transformations in terms of **existing** area and meeting points
- tour areas can **overlap**
- **several** agents can share the **same** trajectory
- simple **bouncing / crossing** rules and **local** knowledge can lead to powerful transformations

- definition of **metrics** to evaluate **transformations**:
  - **average scanning rate**, esp. areas with suboptimal rates
  - **information propagation**, esp. in relation to geometric distances
- definition of **specific** transformations:
  - for **regular** and **non regular** tour network graphs
  - implemented as **distributed protocols**
- implementation of a Java based **simulator**:
  - **simulation** of transformations
  - **evaluation** of metrics
  - **visualization** of network behavior
- **tour-based** design of sample **missions**
- investigations of **formal models** for group-based computations (self-similar algorithms, population protocols)
- **field** experiments with **Sun Spots** mounted on **Roombas**