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Experimental Method and Benchmarking in Mobile Robot Networks

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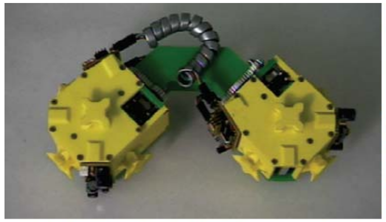
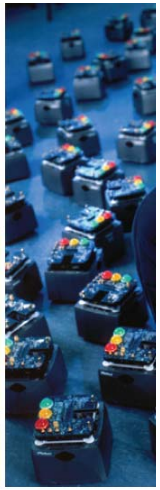
Towards Replicable Experiments in Robotics Research

Outline

- Introduction
- Experiment design for behavior-based approaches
- Modeling of robot networks
- Benchmark of robustness and evaluation tasks
- Conclusions and future work

Introduction





- What are robot networks?
  - multiple robots operating together coordinating and cooperating by networked communication to accomplish a specified task.
    - Capable (beyond capabilities of single robots)
    - Fast (working in parallel)
    - Extensive (Harnessing physically removed assets)
    - Robust (fault tolerance)
    - Efficient (Improved efficiency)


- Applications
  - Manufacturing
  - Defense
  - Space
  - Domestic robots


Fundamental Challenges

- Complexity increases because
  - Decentralization
    - Perception
    - Computation
    - Action
    - Communication
  - Spatially and temporally distributed
- Control
  - Localized to globalized
  - Inverse problem (e.g. swarming)
- Seamless integration of control, communication and perception
  - Modeling
  - Analysis of stability and robustness
  - Synthesis

Biological Inspirations

- Social characteristics of insects and animals
  - Applied to the design of multi-robot systems
  - Various biological societies-particularly ants, bees, and birds
    - Simple local control rules
    - Development of similar behaviors in cooperative robot systems
- Communication
  - Implicit and explicit communication
  - Effect of communication on the performance
    - benefit for particular types of tasks
    - in many cases, communication of even a small amount of information can lead to great benefit
- Behavior-based control
  - Strong influence on the filed of robot networks

Experiment Design for Behavior-Based Approaches

Multi-Robot Systems

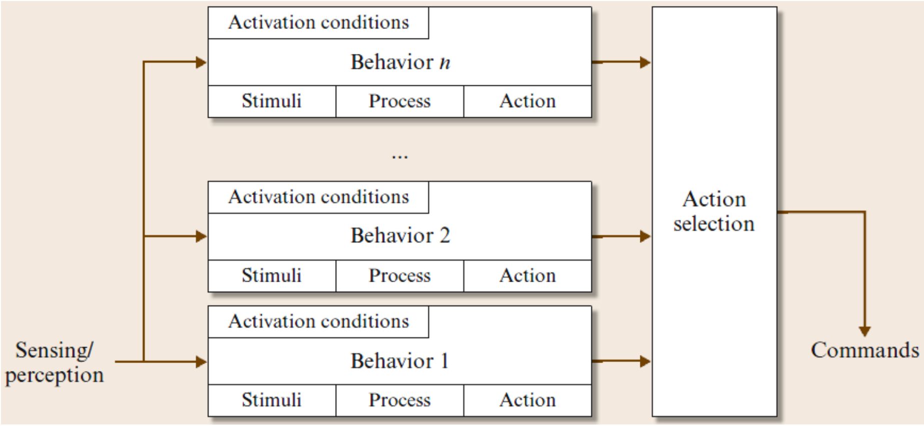
- Robots
  - Mobile robot
  - Local sensing
    - Omni-vision, vision, laser range finder, odometry
  - Global communication
    - Inter-robot wireless communication

- Cooperative tasks
  - Formation
  - Trash collection
  - Robot soccer

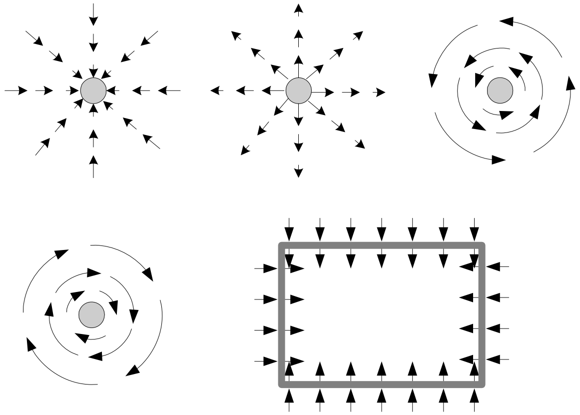
- Environments
  - Unstructured
  - Unknown or partially unknown
  - Dynamic and competitive

Behavioral Control for Robot Individuals

- Motor schema model
  [by Arkin]
  - Integrate many competing behaviors in a coherent whole
  - Integrate in an unique framework data-driven, bottom-up processes
  - Distributed control
- Primary behaviors
  - Move to goal
  - Wander
  - Avoid obstacle
  - Spin around object
  - Avoid boundary
  - …..



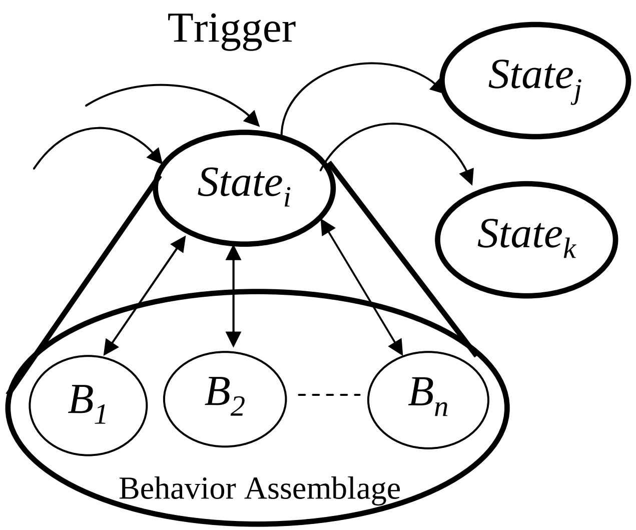
Schematic of behavior-based systems



Primary behaviors

Behavioral Control for Robot Individuals (Cont.)

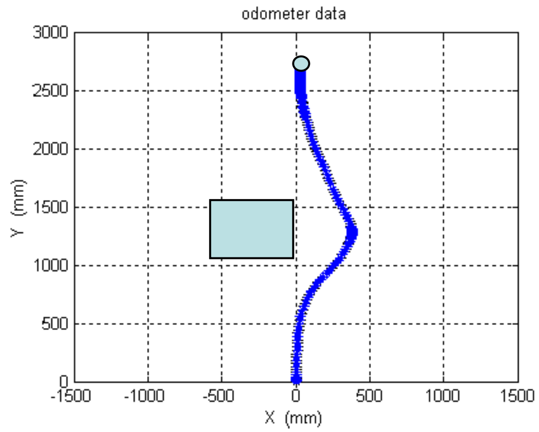
- Task Planning
  - Finite State Automata (FSA)
- Behavior fusion
  - Weighted sum of each active behavior vectors



FSA and behavior fusion

$$\vec{F}_o = \sum_{1}^{n} W_i \vec{B}_i$$

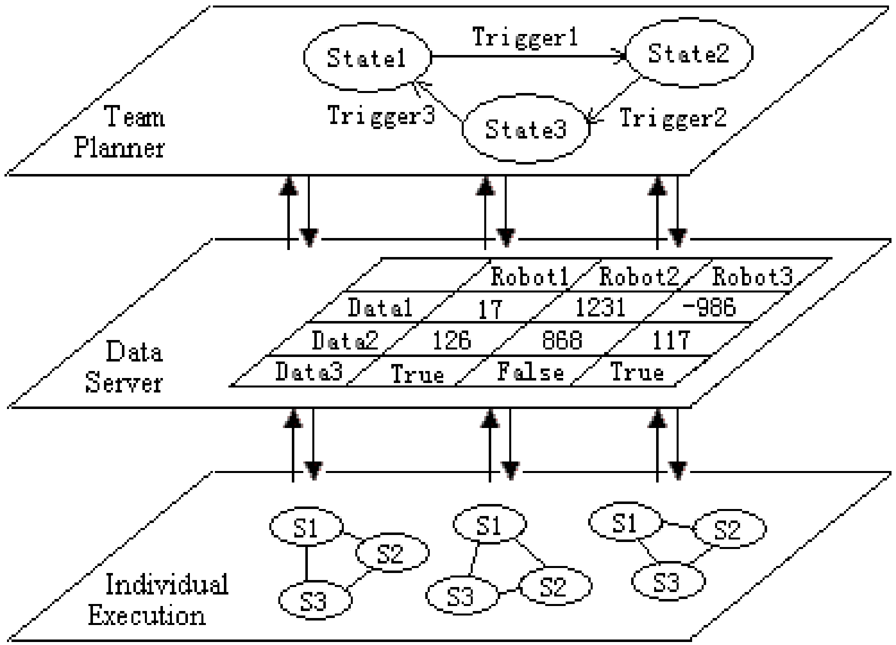
$$\begin{cases} V = V_{\max} \left\| \vec{F}_o \right\| \\ \omega = C \angle \vec{F}_o \end{cases}$$



Move to goal + Avoid obstacle

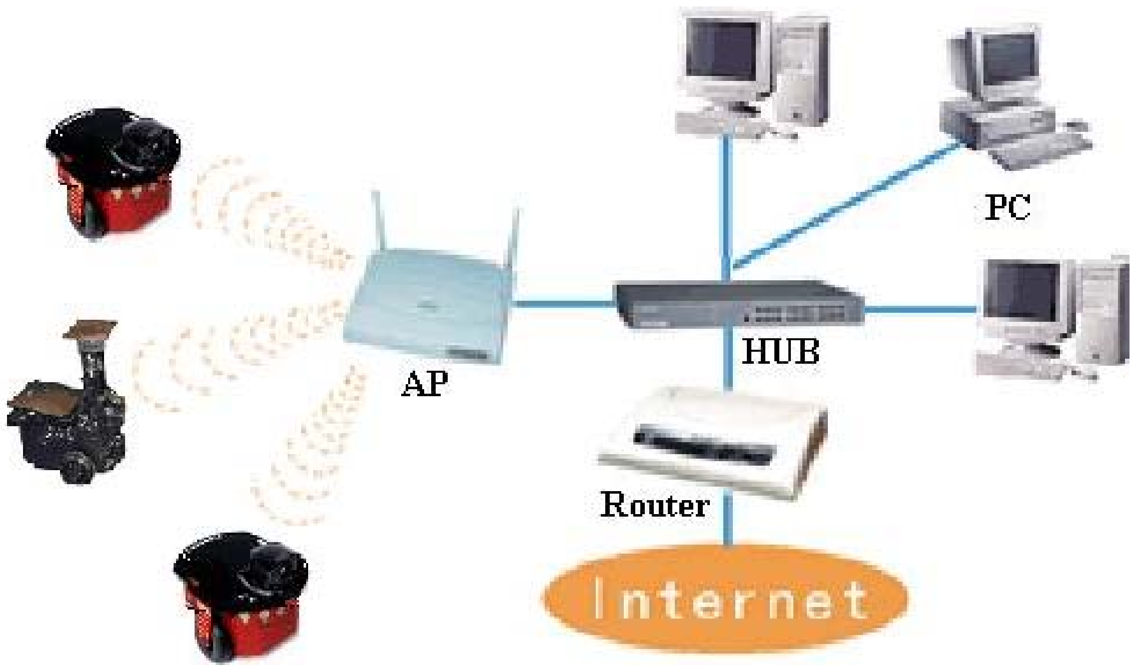
Behavioral Coordination for Robot Networks

- Primary team behaviors
  - Formation keeping
  - Formation switching
  - Leader Following
  - Aggregation
  - Dispersion
  - ……
- FSA based team task planning
  - Environment adaptive formation



Multi-Robot Experiment Platforms

- Heterogeneous multi-robot team
  - Pioneer 2-DX mobile robot
  - Frontier-II mobile robot
- Networking structure



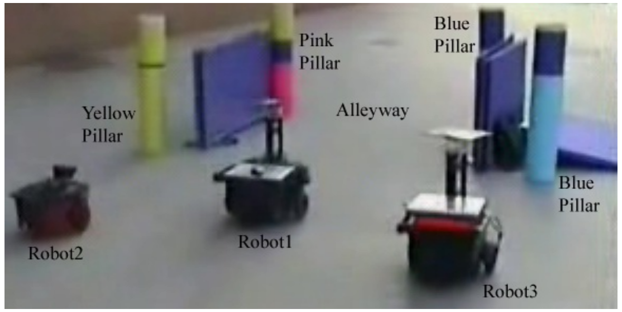
Case Study 1: Multi-Robot Formation

- Behaviors
  - Formation keeping
    - Motor schema
  - Move to goal
  - Avoid obstacle
  - Formation switching

$$V = \sum_{i=1}^{n} w_i V_i \ , \ \omega = \sum_{i=1}^{n} w_i \omega_i$$

$$\sum_{i=1}^{n} w_i = 1$$

- Homogeneous team
  - Video: Obstacle avoidance in formation

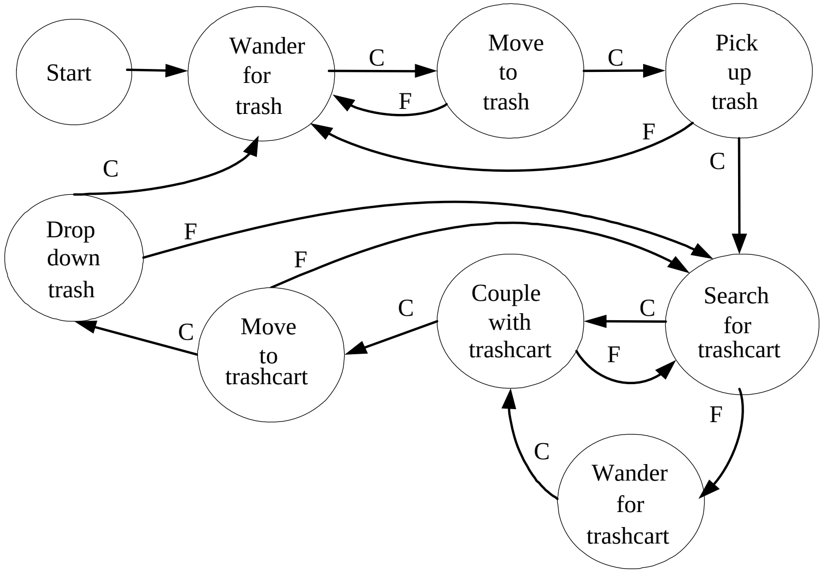


- Heterogeneous team
  - Video: Adaptive formation switching

Case Study 2: Cooperative Trash Collection (I)

- Robot team and task
  - 4 mobile robots
  - Collect the colored cans and deliver to home base

- Role assignment
  - 2 subgroups
  - Each subgroup has a collector and a deliverer (trash-cart)
- Team behaviors
  - Inter-robot collision avoidance
    - Stimulated by sonar
  - Following and coupling
    - Between collector and deliverer
    - Master-slave control mode
    - Stimulated by vision and communication
  - Repulsing
    - Between two subgroups
    - Workspace division
    - Stimulated by vision

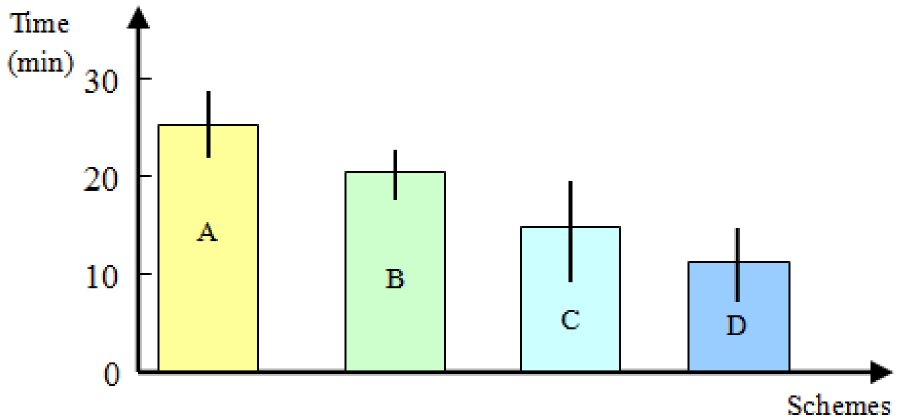


FSA of trash collector

Case Study 2: Cooperative Trash Collection (II)

- Experiments
  - Replicable task and environment
  - Comparison between different schemes
  - Statistical analysis of experimental data

- Performance metrics
  - Time of task completion
  - Traveling distance
  - Uncertainty



Mean time of task completion in different schemes

- Case A: 2 robots, without cooperation
- Case B: 2 robots, with cooperation
- Case C: 4 robots in 2 subgroups, without repulsing between subgroup
- Case D: 4 robots in 2 subgroups, with repulsing between subgroup

- Video: Trash Collection

Case Study 3: Robot Soccer (I)

- Overall RoboCup goal
  - By the year 2050, develop a team of fully autonomous humanoid robots that can win against the human world soccer champion team.

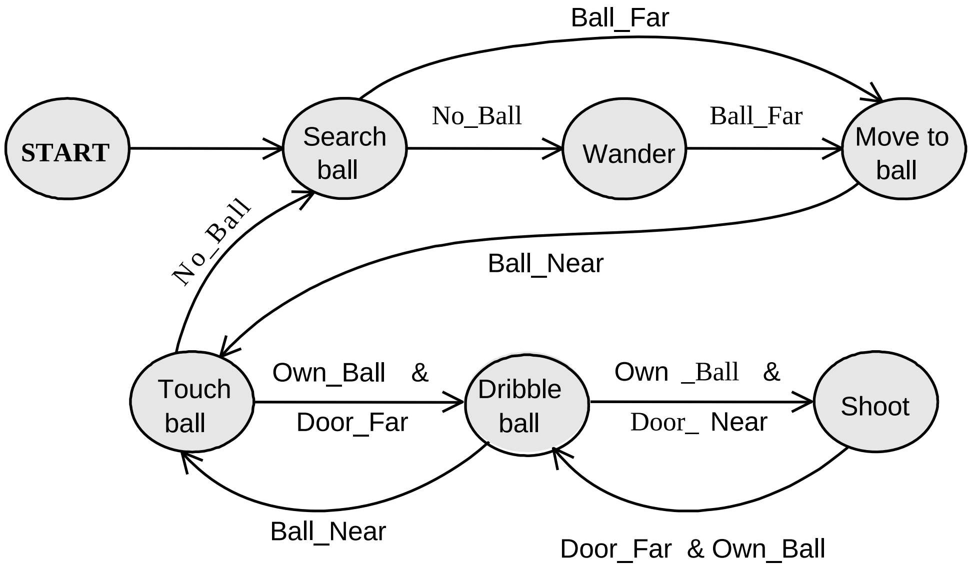
- RoboCup Middle Size League
  - Two teams of mid-sized robots with all sensors on-board play soccer on a field.
  - Relevant objects are distinguished by colors.
  - Communication among robots (if any) is supported on wireless communications.
  - No external intervention by humans is allowed, except to insert or remove robots in/from the field.

- Cooperation in competitive environment

Case Study 3: Robot Soccer (II)

- Team coordinator
- Cooperative perception
  - Cooperative map building
  - Cooperative localization
- Team behavior
  - Defense formation
  - Offence formation
- Role allocation
  - Dynamic role assignment

- Task planning
  - Finite State Automata (FSA)



- Video: JiaoLong-NuBot in RoboCup 2006

FSA of forward player

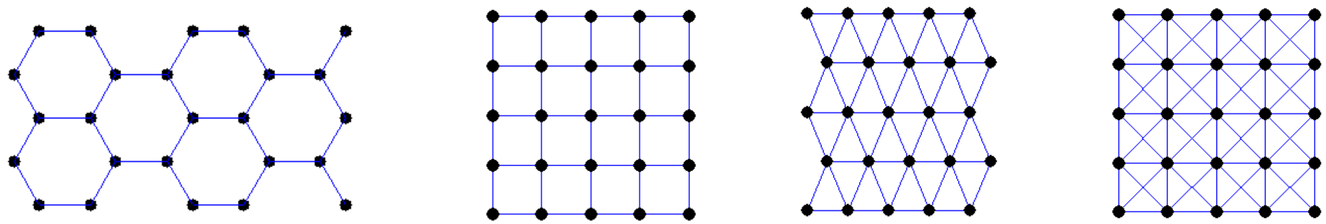
Modeling of Robot Networks

Motivation

- How do we identify and quantify the fundamental advantages and characteristics of robot networks?
- Establish an interaction dynamics model for mobile robot networks
  - Network topology model
  - Individual motion model

Modeling (I)

- Network topology model
  - Graph theory: the coupling matrix $A = (a_{ij}) \in \Re^{n \times n}$
  - *K*-neighbours models



(a) *K*=3 (b) *K*=4 (c) *K*=6 (d) *K*=8

Fig. 1 Four typical topologies of mobile robot networks

$$a_{ii} = -\sum_{j=1, j \neq i}^{n} a_{ij} = -d_i$$

d_i denotes the *degree* of the robot *i*.

Denote the index set of the *neighbors* of the robot *i* as

$$N_e(i) \triangleq \{ j \mid a_{ij} = 1 \} \subseteq \{1, 2, \cdots, n\}$$

Modeling (II)

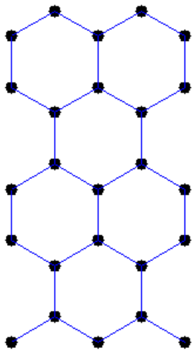
- Individual motion model

Continuous-time dynamics of each mobile robot

$$\begin{cases} \dot{p}_i = x_i, \\ \dot{x}_i = u_i^{\mathrm{e}} + u_i^{\mathrm{c}}, \quad i = 1, 2, \cdots, n, \end{cases} \qquad (1)$$

u_i^{e} stands for effect of the environment upon robot i

$$u_i^{\mathrm{e}} = f(p_i, x_i)$$



u_i^{c} stands for effect of neighboring robots upon robot i

$$u_i^{\mathrm{c}} = c_1 \sum_{j=1}^{n} a_{ij}(k) \cdot (p_j - q_{ij}) + c_2 \sum_{j=1}^{n} a_{ij}(k) x_j, \; i = 1, 2, \cdots, n$$

$c_1, c_2 > 0$ represent the coupling strength of the network

q_{ij} represents the desired relative position of the robots j and i , viewed as the physical topology.

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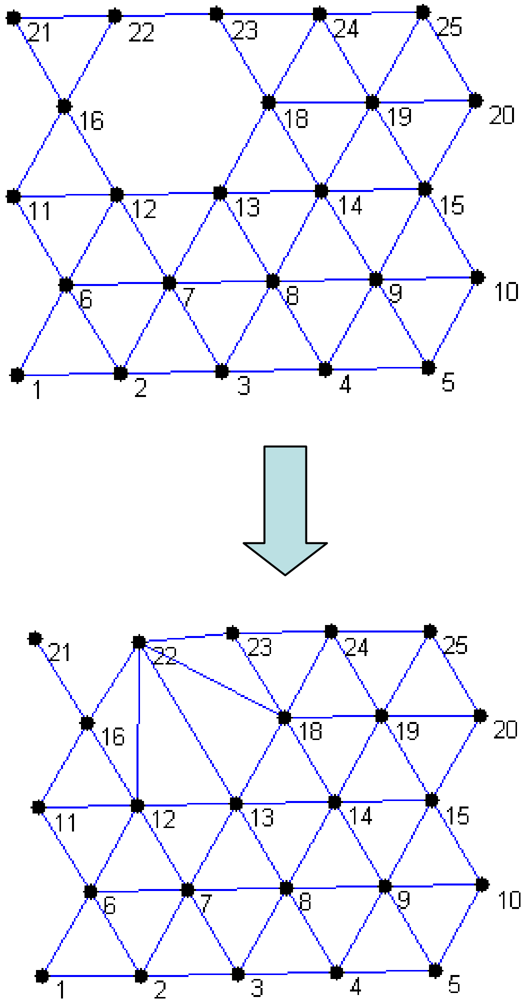
Benchmark of Robustness and Evaluation Tasks

Motivation

- Self-healing
  - It is necessary to self-heal the network topology to prevent the network from being broken with failed robots
  - Process of recovering topologies and system performances of networks from failed robots
- Disadvantage of only self-healing communication topology
  - Higher energy consumption with enlarged communicating range
  - Larger blind zones with finite sensing range for coverage task
- Take advantage of mobility of robots



Topology Control for Self-healing

- Aim of self-healing
  - Substituting robots with lower degree for failed robots with higher degree
- Self-healing rules and algorithm
  - Rule 1
    - Candidates generation: neighbors of the failed robot i_f with lower degree than i_f
  - Rule 2
    - Filling robot selection: the candidate with lowest degree
  - Rule 3
    - Randomly choosing: form the filling robots with the same degree

Stability Analysis

- Achieve synchronous speeds if

$$x_1(t) = x_2(t) = \cdots = x_n(t) \rightarrow v(t), \quad t \rightarrow \infty \qquad (5)$$

- Rewrite the network as a general expression of dynamical networks

1. Suppose $c = c_1 = c_2$

$$\begin{bmatrix} \dot{p}_i \\ \dot{x}_i \end{bmatrix} = \begin{bmatrix} x_i \\ f(p_i, x_i) \end{bmatrix} + c\sum_{j=1}^{n} a_{ij}(k) \begin{bmatrix} 0 & 0 \\ I_N & I_N \end{bmatrix} \begin{bmatrix} (p_j - q_{ij}) \\ x_j \end{bmatrix}, \qquad (6)$$

2. Denote $\Gamma = \begin{bmatrix} 0 & 0 \\ I_N & I_N \end{bmatrix}$ and $y_i = [p_i - q_i \quad x_i]^T \in \Re^{2N} \quad i = 1, 2, \cdots, n,$

   Rewrite the network as:

$$\dot{y}_i = F(y_i) + c\sum_{j=1}^{n} a_{ij}(k)\Gamma y_j, \; i = 1, 2, \cdots, n, \quad k = s(t), \quad A(k) \in \Omega \quad (7)$$

Stability Analysis

- Stability condition
  - The exponential stability of (8) is transformed to the exponential stability of the system

$$\dot{\omega} = [DF(s) + c\lambda_i(k)\Gamma]\omega, \qquad i = 1, 2, \cdots, n, \quad k = s(t) \qquad (12)$$

  - System is stable if the inequality should hold

$$L_{\max}(\lambda_i(k)) = h_{\max} + c\lambda_2(k) < 0, \quad i = 2, \cdots, n, \quad k = s(t) \qquad (13)$$

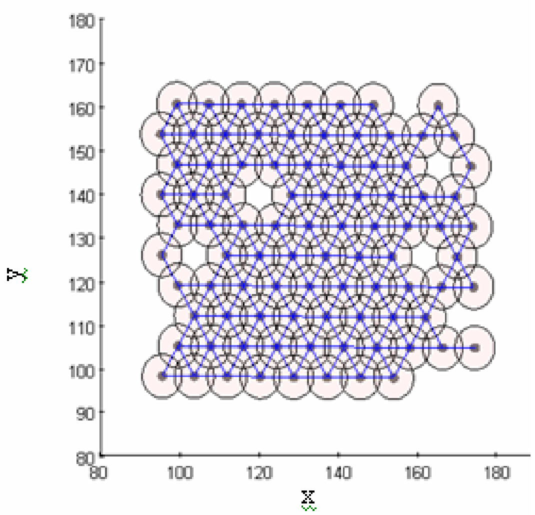
  - Stability condition for the synchronized states of (8) is

$$c > \frac{h_{\max}}{|\lambda_2(k)|} \qquad (14)$$

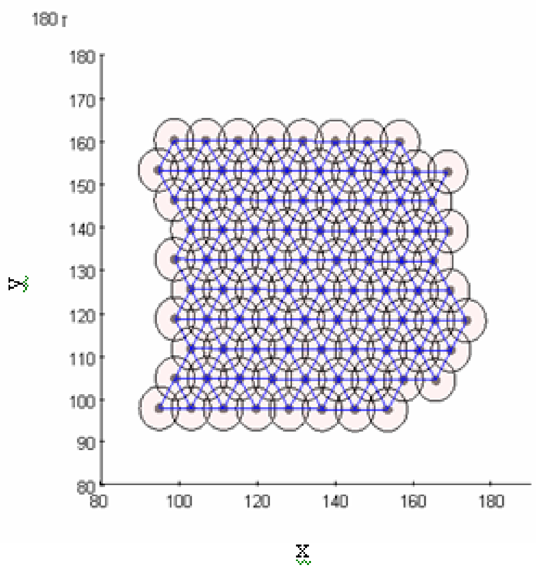
  - A sufficiently large c guarantees the synchronizability of the network

Simulation

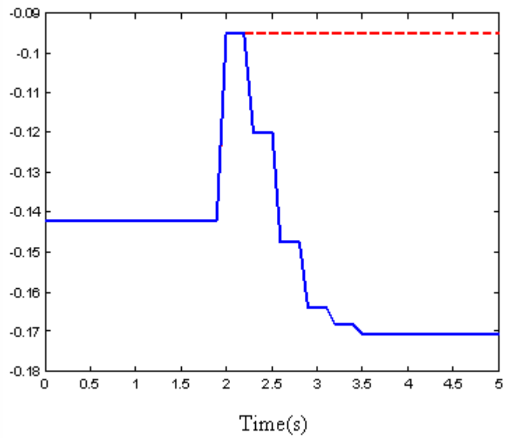
- Self-healing for 10 failed robots
  - n=100
  - The blind zones of sensing in the network decreases.
  - The second-largest eigenvalue of the coupling matrix is maintained almost fixed
- [Video: self-healing 10]



(a) Topology before self-healing



(b) Topology after self-healing



5 Second-largest eigenvalue of coupling matrix in the case of self-healing for failed robots.

Conclusions and Future Work

- The hierarchical architecture combining deliberative planning and behavior-based control is powerful and practical for controlling robot networks.
- The methods for experimental system setup, benchmark tasks, performance metrics are provided.
- A stability and robustness analysis methods are proposed for mobile robot networks based on interaction dynamics model.
- Statistically experimental data are important for revealing the true performance and uncertainty factors.
- The field of robot networks is still so new that no topics area within this domain can be considered mature.
- Real-world experiments
  - Close to practical applications: mapping and localization, search and rescue,……
  - Close to real-world environments: indoor to outdoor, 2D to 3D, small-scale to large-scale,……

Thank you!