Experimental Method and Benchmarking in Mobile Robot Networks

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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
  – …
Behavioral Control for Robot Individuals (Cont.)

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

\[ \vec{F}_o = \sum_{i=1}^{n} W_i \vec{B}_i \]

\[ \begin{align*}
V &= V_{\text{max}} ||\vec{F}_o|| \\
\omega &= C \angle \vec{F}_o
\end{align*} \]

FSA and behavior fusion

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

- Homogeneous team
  - Video: Obstacle avoidance in formation

- Heterogeneous team
  - Video: Adaptive formation switching

\[
V = \sum_{i=1}^{n} w_i V_i, \quad \omega = \sum_{i=1}^{n} w_i \omega_i
\]

\[
\sum_{i=1}^{n} w_i = 1
\]
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

![Bar chart showing mean time of task completion in different schemes]

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

![Fig. 1 Four typical topologies of mobile robot networks](image)

\[ a_{ii} = -\sum_{j=1, j \neq i}^{n} a_{ij} = -d_i \quad d_i \text{ denotes the } \text{degree} \text{ of the robot } i. \]

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

\[ N_e(i) \triangleq \{ j \mid a_{ij} = 1 \} \subseteq \{1, 2, \ldots, n\} \]
Modeling (II)

• Individual motion model

Continuous-time dynamics of each mobile robot

\[
\begin{align*}
\dot{p}_i &= x_i, \\
\dot{x}_i &= u^e_i + u^c_i, \quad i = 1, 2, \ldots, n,
\end{align*}
\]

(1)

- \(u^e_i\) stands for effect of the environment upon robot \(i\)

- \(u^e_i = f(p_i, x_i)\)

- \(u^c_i\) stands for effect of neighboring robots upon robot \(i\)

- \(u^c_i = \sum_{j=1}^{n} a_{ij}(k) \cdot (p_j - q_{ij}) + \sum_{j=1}^{n} a_{ij}(k)x_j, \quad i = 1, 2, \ldots, n\)

- \(c_1, c_2 > 0\) 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.
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

\[ x_1(t) = x_2(t) = \cdots = x_n(t) \rightarrow \nu(t), \quad t \rightarrow \infty \quad (5) \]

- Rewrite the network as a general expression of dynamical networks

1. Suppose \( c = c_1 = c_2 \)

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

2. Denote \( \Gamma = \begin{bmatrix}
0 & 0 \\
I_N & I_N
\end{bmatrix} \) and \( y_i = [p_i - q_i, x_i]^T \in \mathbb{R}^{2N} \) \( i = 1, 2, \ldots, n \),

Rewrite the network as:

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

• Stability condition
  – The exponential stability of (8) is transformed to the exponential stability of the system
    \[ \dot{\omega} = [DF(s) + c\lambda_i(k)\Gamma]\omega, \quad i = 1, 2, \ldots, n, \quad k = s(t) \]
  – System is stable if the inequality should hold
    \[ L_{\text{max}}(\lambda_i(k)) = h_{\text{max}} + c\lambda_2(k) < 0, \quad i = 2, \ldots, n, \quad k = s(t) \]
  – Stability condition for the synchronized states of (8) is
    \[ c > \frac{h_{\text{max}}}{|\lambda_2(k)|} \]
  – 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

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!