Multi-Robot Decision Making: State Estimation and Coordination

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Why Multiple Robots?

- Faster execution
- More robust
- Simplify design of robots
- Task requires it
Why Not Multiple Robots?

- Communication
- More complexity
- Harder to test
- $N \times$ the trouble
- Expensive

Tasks for Multi-Robot Teams

- Mapping and exploration
- Hazardous clean-up
- Reconnaissance
- Tracking

Loosely-coordinated

Map created by robot team.
Tasks for Multi-Robot Teams

- Robot soccer
- Carrying objects
- Large-scale construction
- Constrained exploration
- Coordinated Reconn.

Tightly Coordinated

The Coordination Spectrum

Loosely-Coordinated
- Decomposable into subtasks
- Independent execution
- Minimum interaction
- Task decomposition and allocation strategies.

Tightly Coordinated
- Tasks not decomposable
- Coordinated execution
- Significant Interaction
Taxonomy of Approaches

Centralized
- Fully Centralized

Distributed
- Centralized Allocation
- Emergent
- Intentional
- Hybrid
- Reactive
- Behavior-Based

Multi-Robot Soccer Teams

CMUnited, CMDragons
wheeled, offboard perception & control

CMTrio, CMPack, CMDash
AIBOs, 4-legged, fully autonomous

CMBalance:
Segway soccer human-robot teams
(with B. Browning et al.)
Robot Autonomy: Teams of Robots

CMDragons’15
RoboCup World Champions
Total: 48-0 goals

Robot Soccer:
A Multi-Dimensional Problem

Vision
Path Planning

Ball Manipulation
Defense...
RoboCup “Small-Size” League
Centralized Perception, Cognition, and Distributed Action

[Stefan Zickler et al, RoboCup 2009],
[James Bruce at al, IROS 2000]

SSL-Vision Robot Patterns

[James Bruce & Manuela Veloso, ICRA 2003]
SSL-Vision GUI – Color Calibration

SSL Perception Output: Input to Planner

- For each robot (up to 12)
  - \((x, y, \theta, c)\) field position and orientation and confidence
  - \((p_x, p_y, c)\) image position and confidence

- For the ball (as many as seen, usually/hopefully one!)
  - \((x, y, c)\) field position, projected on the field
  - orange pixels position in image
  - (challenging “chip kick” detection)
World State Estimation

• 1. Multiple Extended Kalman-Bucy Filters track each robot and the ball
• 2. To counter radio latency, world state is forward-predicted to plan for the instant the robots will receive the commands
• 3. Sensing rate is 60 Hz, control loop is at 60Hz, sensing to actuation latency 95ms, hence plan for 95ms in the future – use all sensing and control for prediction

Resulting world state includes predicted positions and velocities of robots and ball.

EKF-Based Forward-Predicted States
Statement of the Planning Problem

- Given a world state, with N (up to 6) teammates, and M (up to 6) opponents,

- Plan for actions to all our robots, in order to maximize the chance of scoring a goal and minimize the chance of the opponent scoring.
Skills-Tactics-Evaluation-Plays (STEP)
Behavior Architecture

Based on the STP architecture (CMDragons’05)
Hierarchical solution to the multi-robot coordination role selection and assignment problem:

- **Plays**: robot roles with applicability conditions
- **Tactics**: execution plans of the roles
- **Evaluation for role assignment and action selection**
- **Skills**: low-level controllers used by tactics

**Plays**

PLAY Attack2OurSide
GAMESTATE game_on
PRECOND contended our_side

ROLE 0
4.0 Attacker;

ROLE 1
0.2 PositionForPass (-1500 0) (3000 4000);

ROLE 2
1.0 PrimaryDefense;

ROLE 3
0.1 SecondaryDefense;

ROLE 4
1.0 PrimaryDefense;

ROLE 5
1.0 Goalie;

Name of the play
Game state and preconditions
Attacking roles with placements
Defending roles
Transitioning Between Plays: Example

**Attack 2 (Our Side)**
- 2 Attacking Roles, Our Side
- 1 Secondary Defense Roles
- 3 Primary Defense Roles

Ball On Our Side, No Possession

**Attack 3 (Our Side)**
- 3 Attacking Roles, Our Side
- 0 Secondary Defense Roles
- 3 Primary Defense Roles

Gained Ball Possession

**Attack 3 (Their Side)**
- 4 Attacking Roles, Their Side
- 0 Secondary Defense Roles
- 2 Primary Defense Roles

Ball On Their Side

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Example Tactic: Simplified Attacker

**Start**

Get Near Ball  
Intercept Ball  
Dribble Ball

Aim  
Shoot  
Done
Skills

- Get Near Ball
- Intercept Ball
- Dribble Ball
- Aim
- Shoot
- Done

STEP Architecture

- Modular
- Flexible
- Skill reuse beyond robot soccer
- Multi-robot play adaptation
- Evaluation sensitive to precise state
Selectively Reactive Coordination (SRC)

Divide planning into two layers:

1. **Coordinated opponent-agnostic layer**
   - Team commits to *plan skeleton*

2. **Individual opponent-reactive action selection layer**
   - Team member chooses *individual actions* consistent with plan skeleton

Selectively Reactive Coordination (SRC) for Team Offense Planning

- Our solution: layered SRC
  1. **Opponent-agnostic** team coordination layer
  2. **Opponent-reactive** individual action evaluation and action selection layer

- Layered planning:
  1. Use predefined computation for *zones* for Support Attackers with predefined positioning in zones
  2. Optimally assign 1 robot to PA, and n-1 robots to SA with predefined zones.
  3. Each robot individually selects its optimal action.
Opponent-Agnostic Layer

Zone Selection 2: Dynamic Zones
Estimating $P(\text{goal} | a, x)$

$P(\text{goal} | \text{sh}, x) = 0$

$P(\text{goal} | \text{pass}, x) = P(\text{goal} | \text{shoot}, x') \times P(\text{receive}(x') | x, \text{pass})$

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Pass Ahead Coordination:

Case 1: $T_r < T_p$

If $T_r < T_p$, passer P starts maneuvering.
Receiver R waits.

Once $T_r = T_p$, both R and P proceed.
Pass Ahead Coordination:

Case 2: $T_r > T_p$

If $T_r > T_p$, receiver R starts moving.
Passer P waits.

Once $T_r = T_p$, both R and P proceed.

RoboCup 2015 Results:
Effective coordinated offense

• Offense effectiveness:
  – Won all 3 practice games (5-0, 8-0, 10-0)
  – Won all 3 round-robin tournament games (6-0, 10-0, 10-0)
  – Won all 3 playoff games (15-0, 2-0, 5-0)

• Coordination effectiveness:
  – 79.2% pass completion rate
Autonomous Robots

- Teams of 4 robots (initially 3 robots)
- Remarkable hardware - SONY AIBO robots
- Sensing, computing, and communication onboard
- Fully distributed - world modeling

Coordination without Communication

- Videos – history
- Discussion
  - Coordination how?
Teamwork Without Communication

• Team is a set of *individual* robots
• View of the world solely from *own* sensors
• Teamwork achieved through *predefined roles*
  • Attacker: “Can I see the ball? Go to the ball. Where am I? And where is the goal? Kick ball to goal.”
  • Goalie: “Can I see the ball? Is the ball next to me? Clear the ball. Where am I? Go back to defend goal.”

Teamwork With Communication

• Team is still a set of *individual* robots
• Model of the world from *own* sensors and *communicated* information from team members.
  – Communication based on own sensing
State

- Own State – processed sensory data
  - “big” vector of task-relevant quantities:
    - **Relative** distance to task-relevant objects
      • Ball, goal, other robots, landmarks

- Sharing State – need localization
  - Position in *absolute* referential space for common “language”

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Robot’s Position – Localization

- *Apriori*: motion model, map
- *Given*: actual motion, sensing
- *Compute*: probabilistic distribution of position belief
- *Method*: Bayesian update
Multi-Robot World Modeling

- Communication with latency
- Noise and confidence in shared information
- Multiple (variable) teammates

Challenge: Combine local and communicated information to form a coherent *world model*

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Tracking

- Control to track *seen* and *unseen* object resulting from *own* and *shared* perception
- Example:
  - Where is the ball?
Tracking Using Own Sensing

- Action models include probabilistic effects
- Effects are visited in order according to their probability

Distributed State Estimation

*RMH: Ranked Multi-Hypothesis*

- Use own perception
- If object not in own view:
  - Generate a probabilistic set of hypotheses
    - Nondeterministic models of own actions
    - Teammate shared sensory data
    - ...
  - Rank the hypotheses according to a confidence and utility function
  - Visit in order the ranked hypotheses
Given Common World Model, Multi-Robot Coordination

1. Role assignment
   - Primary attacker, offensive supporter, defensive supporter

2. Strategic positioning
   - Environment driven gradient field

Roles

- Role: Specific set of behaviors that one member of the team will execute
  - Responsible for completing a task
  - Respond to a specific set of contingencies
- Roles can have overlapping responsibilities
- The assignment of roles to robots can be static or dynamic
Market-Based Approaches

- Robots model an economy:
  - Accomplish task → receive revenue
  - Consume resources → incur cost
  - Robot goal: maximize own profit
  - Trade tasks and resources over the market (auction!)
- By maximizing individual profits, team finds better solution
- Time permitting, more centralized
- Limited computational resources, more distributed

A Simple Example:

Max Reward = 120  Max Reward = 180

<table>
<thead>
<tr>
<th>Robot</th>
<th>tA</th>
<th>tB</th>
</tr>
</thead>
<tbody>
<tr>
<td>Robot 1</td>
<td>50</td>
<td>100</td>
</tr>
<tr>
<td>Robot 2</td>
<td>No bid</td>
<td>70</td>
</tr>
</tbody>
</table>

Profit: 70  Profit: 110

System cost: 50 + 70 = 120
A Simple Example:

Max Reward = 120
Max Reward = 180

<table>
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<td>50</td>
<td>100</td>
<td>110</td>
</tr>
<tr>
<td>Robot 2</td>
<td>No bid</td>
<td>70</td>
<td>170</td>
</tr>
</tbody>
</table>

System cost: 50+70=120
System cost: 50+60=110

Bids Placed for Tasks

Robot 1
Profit: 70
Profit: 190

Robot 2
Profit: 110
Profit: 0

Summary

- Teamwork
  - Without communication
  - With communication

- World state sharing
- Positioning
- Role assignment
  - Bidding: auction