Multi-Robot Decision Making:
State Estimation and Coordination

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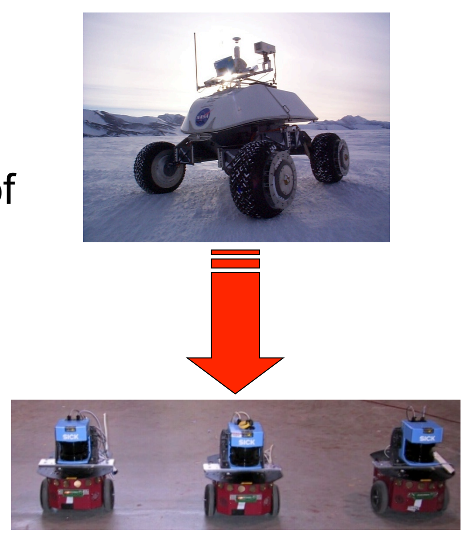
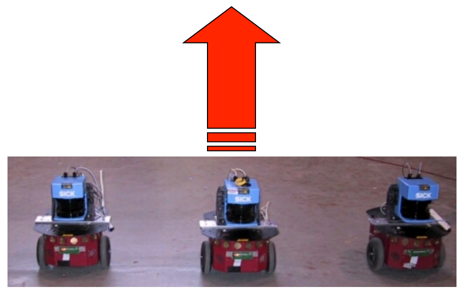
Why Multiple Robots?

- Faster execution
- More robust
- Simplify design of robots
- Task requires it



Why *Not* Multiple Robots?

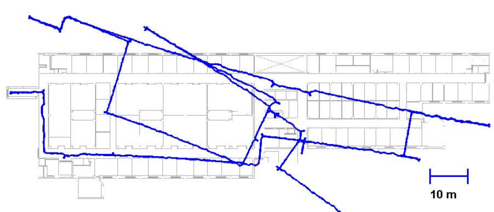
- Communication
- More complexity
- Harder to test
- N x the trouble
- Expensive



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

◀ Robotic Construction.

Box Carrying ▶

The Coordination Spectrum

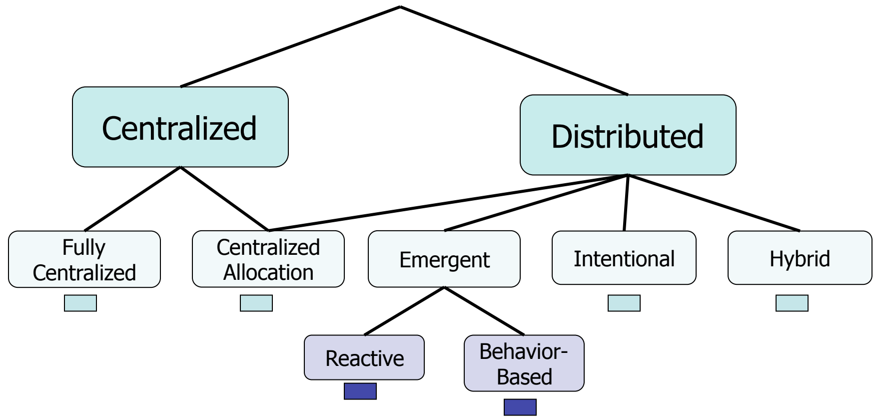
Loosely-Coordinated

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

Tightly Coordinated

- Tasks not decomposable
- Coordinated execution
- Significant Interaction

Taxonomy of Approaches

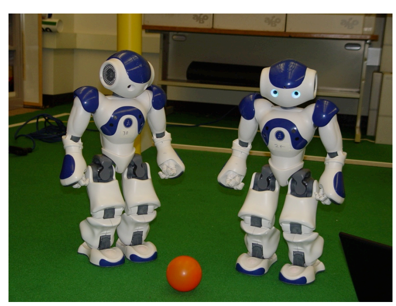


Multi-Robot Soccer Teams

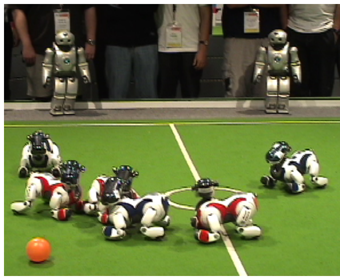
CMUnited
CMDragons
wheeled, offboard perception & control

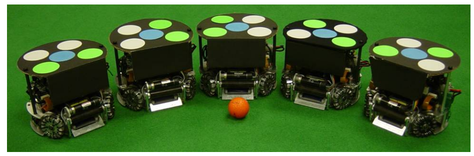
CMTrio, CMPack, CMDash
AIBOs, 4-legged, fully autonomous

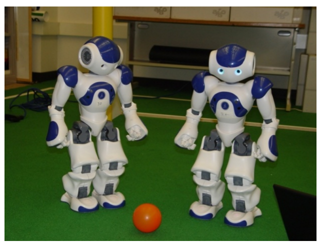
CMBalance: Segway soccer human-robot teams
(with B. Browning et al.)



Robot Autonomy: Teams of Robots



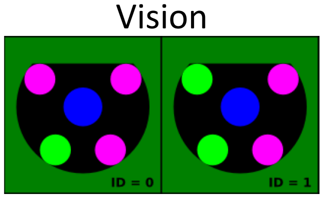




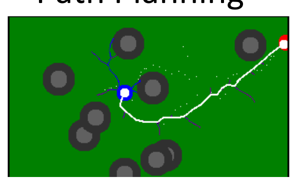
CMDragons'15
RoboCup World Champions
Total: 48-0 goals

Robot Soccer: A Multi-Dimensional Problem

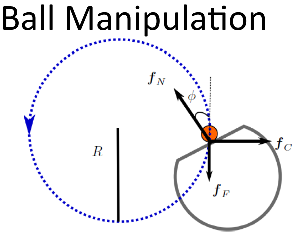
Vision



Path Planning



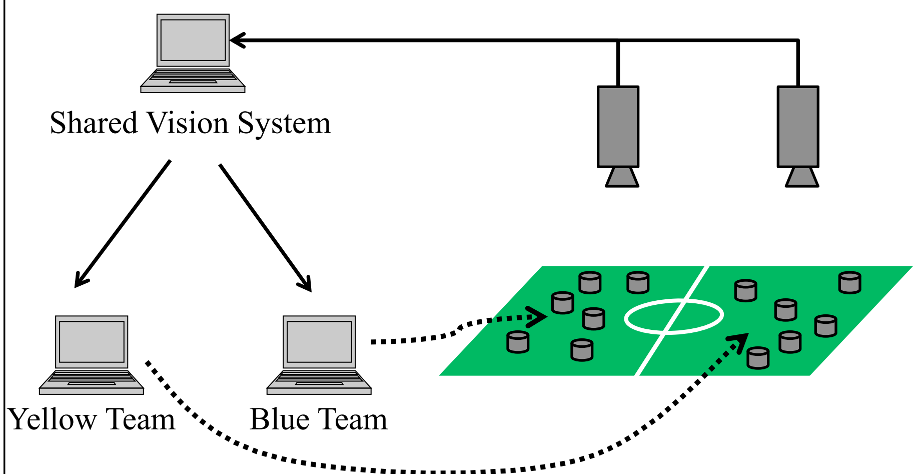
Ball Manipulation



Defense…

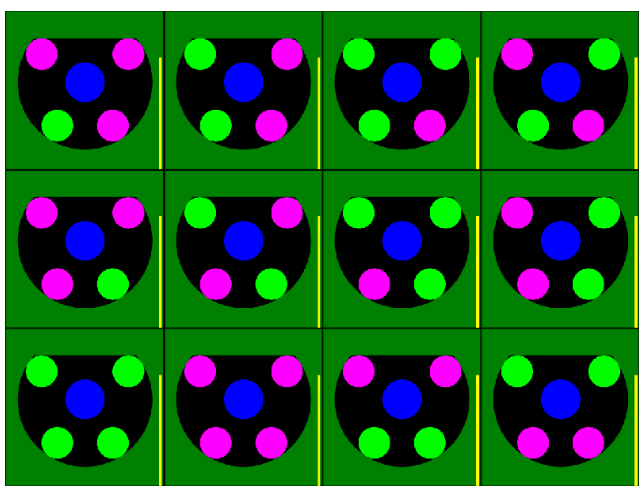
RoboCup "Small-Size" League

Centralized Perception, Cognition, and Distributed Action



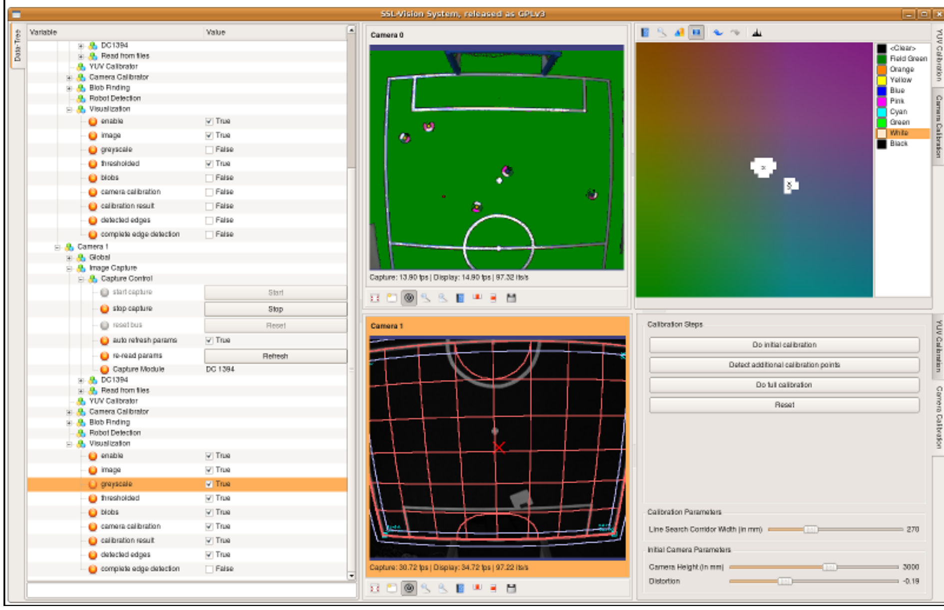
[Stefan Zickler et al, RoboCup 2009],
[James Bruce at al, IROS 2000]

SSL-Vision Robot Patterns



[James Bruce & Manuela Veloso, ICRA 2003]

SSL-Vision GUI – Color Calibration



SSL Perception Output: Input to Planner

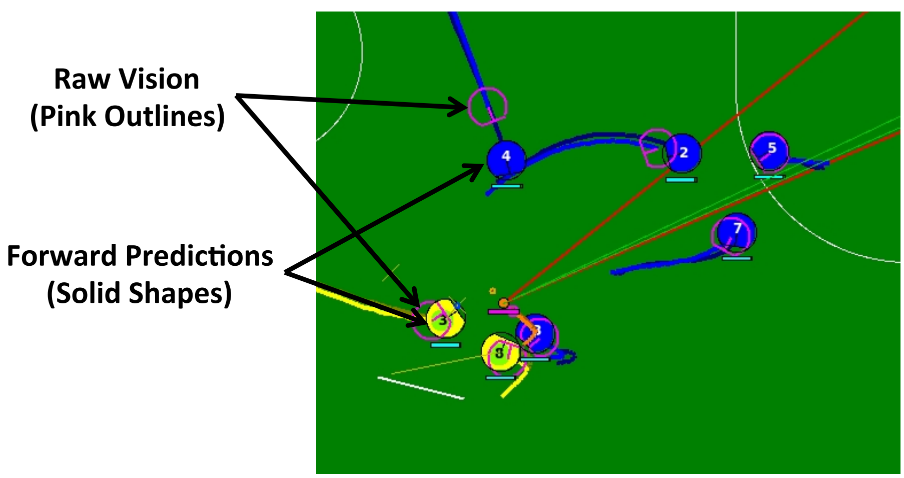
- For each robot (up to 12)
  - (x, y, θ, c) field position and orientation and confidence
  - (p_x, $p_{y,}$ c) image position and confidence
- For the ball (as many as seen, usually/hopefully one!
  - (x, y, c) field position, projected on the field
  - orange pixels position in image
  - (challenging “chip kick” detection)

World State Estimation

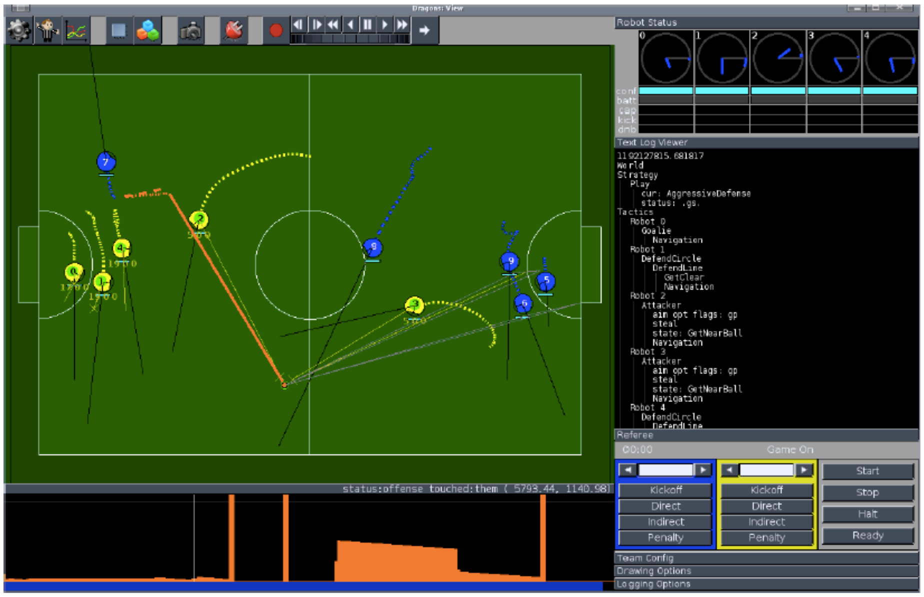
- 1. Multiple Extended Kalman-Bucy Filters track each robot and the ball
- 2. To counter radio latency, world state is forward-predicted to plan for the instant the robots will ***receive*** the commands
- 3. Sensing rate is 60 Hz, control loop is at 60Hz, sensing to actuation latency 95ms, hence plan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



Logging, GUI, Layered Disclosure



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;
```

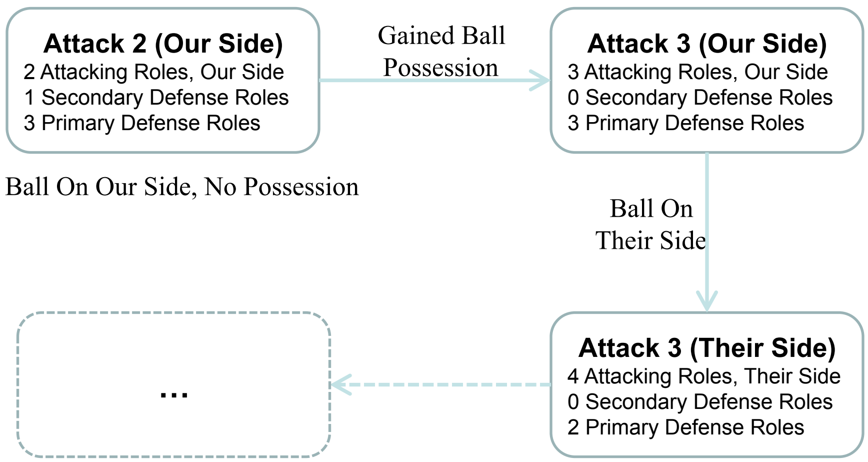
← Name of the play

← Game state and preconditions

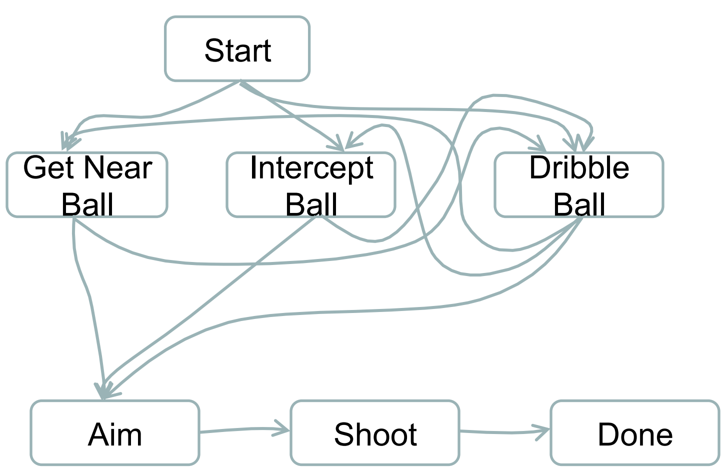
} Attacking roles with placements (ROLE 0 – ROLE 1)

} Defending roles (ROLE 2 – ROLE 5)

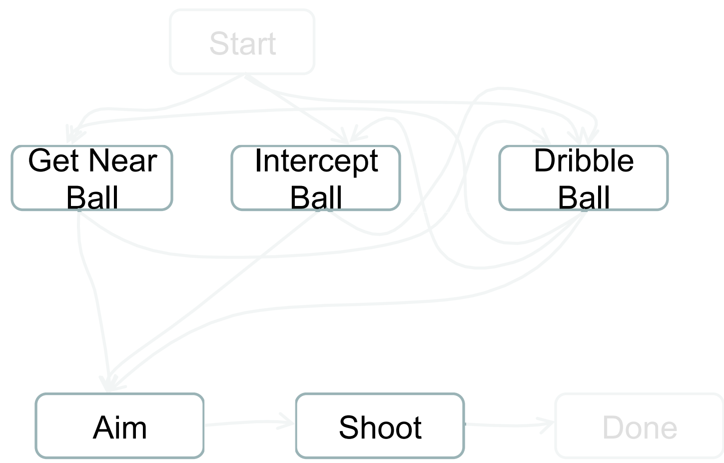
Transitioning Between Plays: Example



Example Tactic: Simplified Attacker



Skills



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*

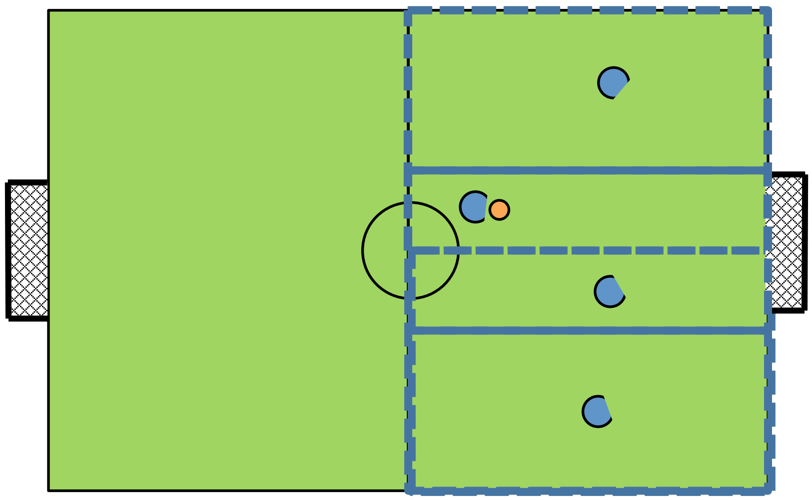
2. **Individual opponent-reactive action selection layer**
   - Team member chooses *individual actions* consistent with plan skeleton

Selectively Reactive Coordination (SRC) for Team Offense Planning

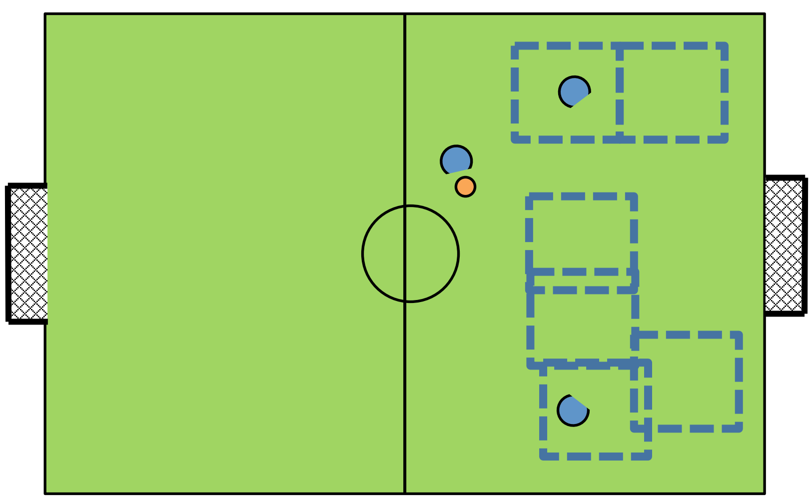
- Our solution: layered SRC
  1. Opponent-agnostic team coordination layer
  2. Opponent-reactive individual action evaluation and action selection layer

- 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



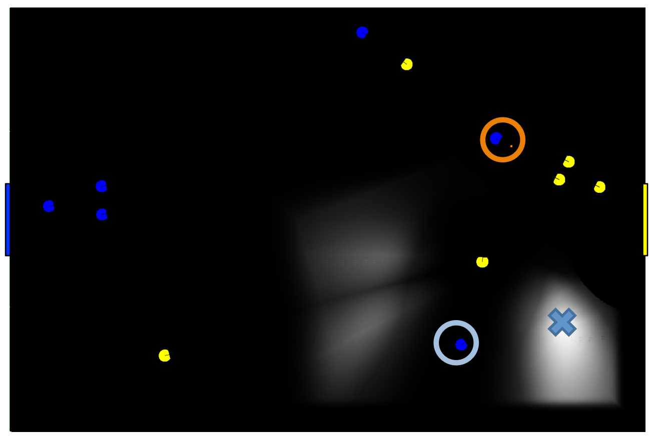
Zone Selection 2: Dynamic Zones



Estimating $P(\text{goal}\,|\,\boldsymbol{a}, \boldsymbol{x})$

$P(\text{goal}\,|\,\textbf{sh}, \boldsymbol{x}) \approx 0$

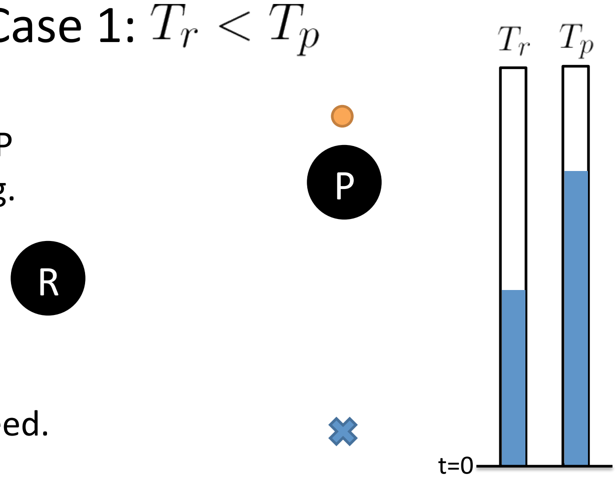
$P(\text{goal}\,|\,\textbf{pass}_i, \boldsymbol{x}) = P(\text{goal}\,|\,\textbf{shoot}, \boldsymbol{x}') \times P(\text{receive}(\boldsymbol{x}')|\boldsymbol{x}, \textbf{pass}_i)$



Pass Ahead Coordination: Case 1: $T_r < T_p$

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

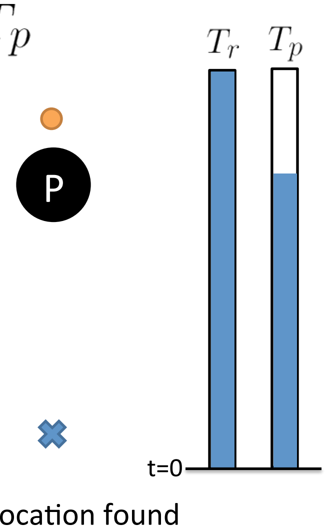
Once $T_r = T_p$, both R and P proceed.



Pass Ahead Coordination:
Case 2: $T_r > T_p$

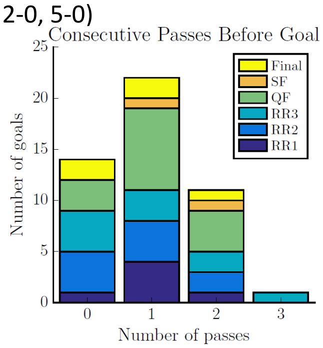
If $T_r > T_p$, receiver R starts moving.
Passer P waits.

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



Carnegie Mellon University

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

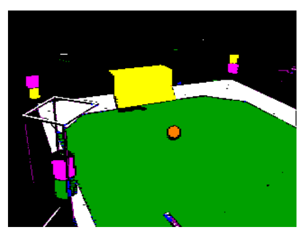
State

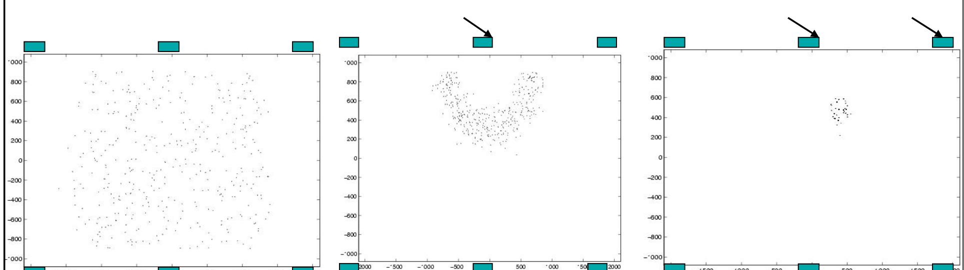
- Own State – processed sensory data
  - “big” vector of task-relevant quantities:
  - ***Relative*** distance to task-relevant objects
    - Ball, goal, other robots, landmarks

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

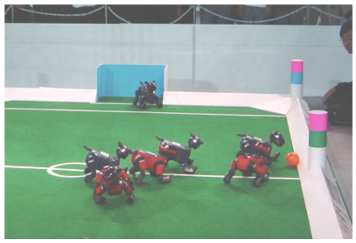
Robot’s Position – Localization

- *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*

Tracking

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

Tracking Using Own Sensing

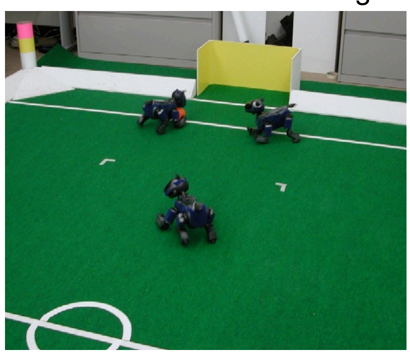
- Action models include probabilistic effects
- Effects are visited in order according to their probability

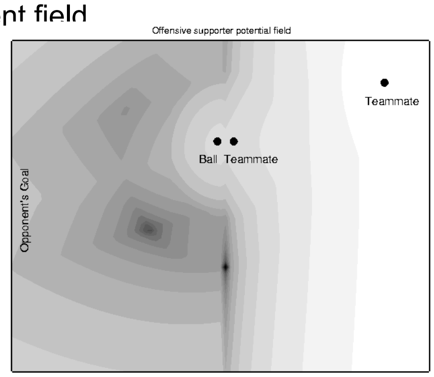
Distributed State Estimation *RMH: Ranked Multi-Hypothesis*

- 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



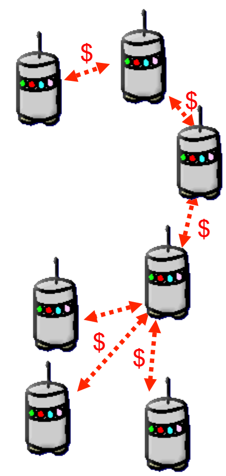


Roles

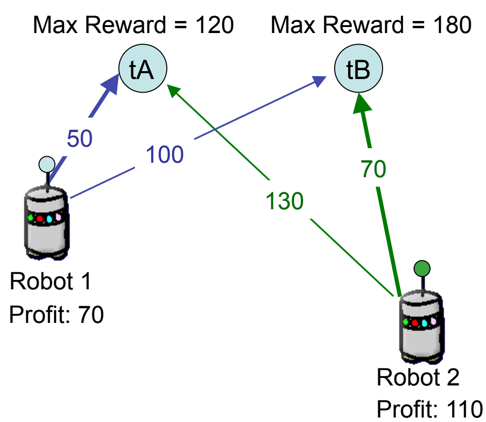
- Role : Specific set of behaviors that one member of the team will execute
  – Responsible for completing a task
  – Respond to a specific set of contengencies
- Roles can have overlapping responsibilities
- The assignment of roles to robots can be static or dynamic

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:

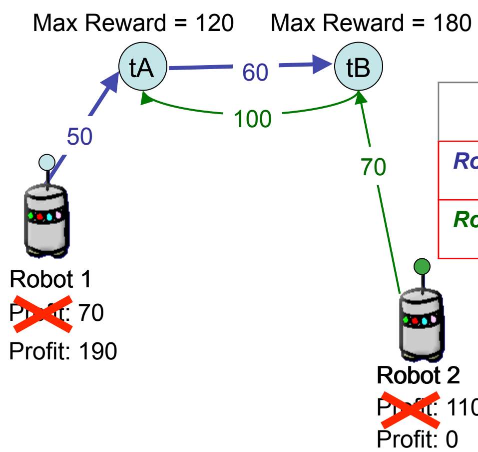


Bids Placed for Tasks

	tA	*tB*
Robot 1	**50** ✓	**100**
Robot 2	**No bid**	**70** ✓

System cost: 50+70=120

A Simple Example:



Bids Placed for Tasks

	tA	tB	tA+tB
Robot 1	50	100	110 ✓
Robot 2	No bid	70	170

~~System cost: 50+70=120~~

System cost: 50+60=110

Summary

- Teamwork
  - Without communication
  - With communication
- World state sharing
- Positioning
- Role assignment
  - Bidding: auction