Multi-Robot Systems

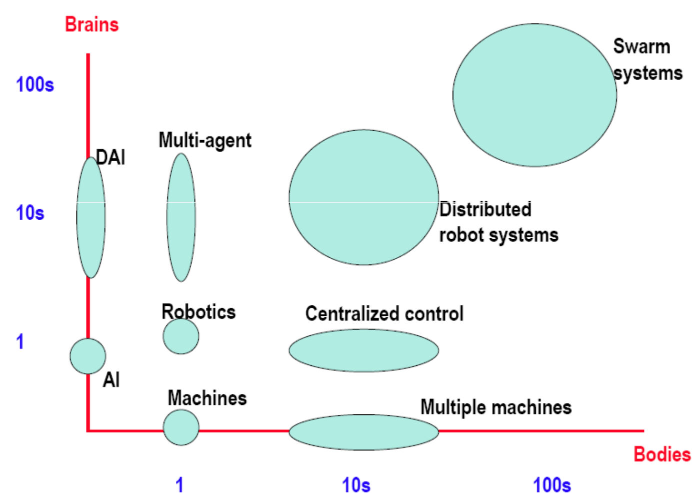
Terminology

- Various rather interchangeable terms are used in this area:
  - Group behavior / robotics
  - Collective behavior / robotics
  - Cooperative behavior / robotics
  - Swarm robotics
  - Multi-robot systems
- Some terms imply larger sizes and/or more or less deliberative approaches; for now the differences can be ignored

Classification According to Interaction

- **Collective:** Even though the robots may not be aware of each other, they share goals and their actions help each other. Swarm robotics inspired by social insects, is a recent and very successful example for this. The robots individually typically have quite simple controllers, nevertheless due to large number of robots the overall goal can be accomplished.
- **Cooperative:** In this kind of interaction a team of robots is set to accomplish a task working together and they are aware of each other. Whenever tasks are decomposable, subtasks may be allocated to individual robots. The main concerns are optimal task allocation and interference among the robots.
- **Collaborative:** Here a group of robots each with its own agenda compatible with the others try to accomplish tasks. The robots are aware of each other and most likely heterogeneous with different sensor actuator suites.
- **Coordinative:** Even though the robots are aware of each other they do not share a common goal. Typically they inhabit the same workspace with potential for interference. Hence, coordination among them is necessary.
- **Adversarial:** Whenever the robots have goals that have a negative effect on the others we have this kind of interaction. Here typically a team of robots try to accomplish their task in spite of the efforts of yet another team of robots.

Multi-Robot Systems --Brains + Bodies

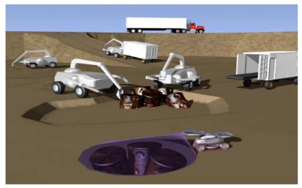


Many Potential Application Domains for Multi-Robot Teams

Space Exploration

Mining

Surveillance and Reconnaissance



Hazardous Waste Cleanup

Primary Areas of Research

- Biological Inspirations
- Motion Coordination
- Communication
- Object Transport and Manipulation
- Reconfigurable Robotics
- Architectures, Task Planning, and Control
- Localization, Mapping, and Exploration
- Learning

Biological Inspirations

- Objective
  - Study biological systems to achieve engineering goals
- Communication
  - Auditory, chemical, tactile, visual, electrical
  - Direct, indirect, explicit, implicit
- Roles
  - Strict division vs. loose “assignments”
- Hierarchies
  - Absolute linear ordering, partial ordering, relative ordering
  - Purpose: reduction in fighting, efficiency
- Territoriality
  - Reduces fighting, disperses group, simplifies interactions
- Social facilitation/sympathetic induction
  - Allows for efficient use of resources
- Imitation
  - Complex mechanism for learning

Motion Coordination

- Objective:
  - enable robots to navigate collaboratively to achieve spatial positioning goals
- Issues studied:
  - Multi-robot path planning
  - Traffic control
  - Formation generation
  - Formation keeping
  - Target tracking
  - Target search
  - Multi-robot docking

Communication

- Objective:
  - Enable robots to exchange state and environmental information with a minimum bandwidth requirement
- Issues studied:
  - Explicit vs. Implicit
  - Local vs. Global
  - Impact of bandwidth restrictions
  - “Awareness”
  - Variety of mediums: radio, IR, chemical scents, “breadcrumbs”, etc

Object Transport and Manipulation

- Objective:
  - Enabling multiple robots to collaboratively push, move, or carry objects that cannot be handled by one robot alone
- Issues studied:
  - Constrained vs. unconstrained motions
  - Two-robot teams versus "swarm"-type teams
  - Compliant vs. non-compliant grasping mechanisms
  - Cluttered vs. uncluttered environments
  - Global system models vs. distributed models

Reconfigurable Robotics

- Objective:
  - Obtain function from shape, allowing modules to (re)connect to form shapes that achieve desired purpose
- Earliest research included reconfigurable/cellular robotics
- Several newer projects:
  - Various navigation configurations (rolling track, spider, snake, etc.)
  - Lattices, matrices (for stair climbing, object support,

Architectures, Task Planning, and Control

- Objective
  - Development of overall control approach enabling robot teams to effectively accomplish given tasks
- Issues studied:
  - Action selection
  - Delegation of authority and control
  - Communication structure
  - Heterogeneity versus homogeneity of robots
  - Achieving coherence amidst local actions
  - Resolution of conflicts

Localization, Mapping, and Exploration

- Objective
  - Enable robot teams to cooperatively build models of their environment, or to accomplish spatial tasks requiring knowledge of other robot positions
- Issues studied:
  - Extension of single-robot mapping approach to multi-robot teams
  - Hardware, algorithms for robot positioning
  - Sonar vs. laser vs. stereo imagery vs. fusion of several sensors
  - Landmarks vs. scan-matching

Learning

- Objective
  - Enable multi-robot teams to adapt or develop own control approach to solve a task with minimal human operator input
- Application domains studied:
  - Predator/prey
  - Box pushing
  - Foraging
  - Multi-robot soccer
  - Cooperative target observation

New Research Areas

- Robot-Agent-People teams as peers
- Heterogeneous teams
- Swarm robotics- large numbers of robots (>=100)

Why Biological Systems?

- Key reasons:
  - Animal behavior defines intelligence
  - Animal behavior provides existence proof that intelligence is achievable
- Typical subjects of study:
  - Ants
  - Bees
  - Birds
  - Fish
  - Herding animals (wolves)

Classification of Animal Societies

- Tinbergen, 1953
- Social Animals
  - Differentiate
  - Integrate

Societies that Differentiate

- Innate differentiation of blood relatives
- Strict division of work and social interaction
- Individuals:
  - Exist for the good of society
  - Are totally dependent on society
- Examples:
  - Bees
  - Ants

Societies that Integrate

- Depend on the attraction of individual animals
- Exhibit loose division of labor
- Individuals:
  - Integrate ways of behavior
  - Thrive on support provided by society
  - Are motivated by selfish interests
- Examples:
  - Wolf packs
  - Bird colonies

Parallels to Cooperative Robotics

- Societies that Differentiate vs Emergent cooperation
  - Large numbers
  - Homogeneous
  - Individual has little capability
  - As a group, generate “intelligent” cooperative behavior
  - Largely ignores issues of efficiency

Parallels to Cooperative Robotics (Cont.)

- Societies that Integrate vs Higher-level cooperation
  - Small numbers
  - Heterogeneous
  - Individual can accomplish meaningful task along
  - Redundancy, complementarity in individual capabilities
  - Often deal with time or energy constraints

Approaches and Tasks

- Differentiating approach:
  - For tasks that require numerous repetitions of same activity over a fairly large area
  - Examples:
    - Waxing floor
    - Removing barnacles off ships
    - Collecting rock samples on Mars
- Integrating approach:
  - For tasks that require several distinct subtasks
  - Examples:
    - Automated manufacturing
    - Industrial/household maintenance
    - Search and rescue
    - Security, surveillance, or reconnaissance (some types)

Swarming / Flocking / Schooling

- Natural flocks consist of two balanced, opposing behaviors:
  - Desire to stay close to flock
  - Desire to avoid collisions with flock
- Why desire to stay close to flock?
  - In natural systems:
    - Protection from predators
    - Statistically improving survival of gene pool from predator attacks
    - Profit from a larger effective search pattern for food
    - Advantages for social and mating activities

Contrasts in Swarming / Flocking / Schooling

- Made up of discrete agents, yet overall motion seems fluid
- Simple in concept, yet visually complex
- Randomly arrayed, yet highly synchronized
- Seems intentional, with centralized control, yet evidence suggests group motion is only due to aggregate result of individual agents

Computational Complexity of Flocking

- Natural systems use a constant time algorithm for flocking
- No indication that flocking is bounded
- Flocks don't become "overloaded" or "full" as new agents join
  - Herring migration: schools are as long as 17 miles and contain millions of fish
- Individual natural agent (e.g., bird) doesn't seem to pay attention to each flockmate
- In birds, seem to be 3 categories of awareness:
  - Itself
  - 2-3 closest neighbors
  - Rest of flock

Advantages of Group Solutions

- Using multiple robots to solve certain tasks can provide great benefits, which include:
  - Improved system performance (usually in terms of speed of completion)
  - Improved task enablement
  - Distributed sensing
  - Distributed action at a distance
  - Fault tolerance through redundancy

Disadvantages of Group Solutions

- The benefits come with a price:
  - Interference between robots
  - Communication cost and robustness
  - Uncertainty regarding other robots' intentions
  - Overall system cost

Potentially useful tasks for robot societies

- Foraging: randomly placed items are distributed throughout the environment, and the team's task is to carry them back to a central location
- Consuming: robots perform work on the desired objects in place. e.g. clearing a land mine field
- Grazing: a robot team cover an environmental area;
  - surveillance operations;
  - search and rescue;
  - cleaning tasks; a vacuum cleaning robot..

Potentially useful tasks for robot societies

- Formations/flocking: robots assume a geometric pattern: e.g. an attack formation to minimize time spent to cross an area or a column formation to follow a road.
- Object transport: distribution of robots around a desired object: the goal is to move it to a particular location.
- Entertainment: robot sports e.g. soccer, robot wars, robot sumo, robot actors etc..

Types of Collective Systems

- Merely Coexisting: multiple robots coexist in a shared environment, but do not even recognize each other, merely as obstacles
  - Advantage: no need for coordination
  - Disadvantage: increased group size results in uncontrolled interference
- Loosely Coupled: multiple robots share an environment and sense each other and may interact, but do not depend on one another; members of the group can be removed without significant effect
  - Advantage: robust
  - Disadvantage: difficult to coordinate for precise tasks
- Tightly Coupled: multiple robots cooperate on a precise task, usually by using communication, turn-taking, and other means of tight coordination
  - Disadvantage: depend on each other ...

Example Domains

- Mere coexistence
  - foraging
- Loosely coupled
  - foraging
  - collection
  - distributed mapping
- Tightly coupled
  - formations
  - moving objects

Competitive Domains

- Besides cooperation there is also competition
- Game scenarios are a good challenge for developing group robotics
  - robot soccer, the grand AI challenge
- Real world scenarios have competitive elements (robots are always competing for space; interference)

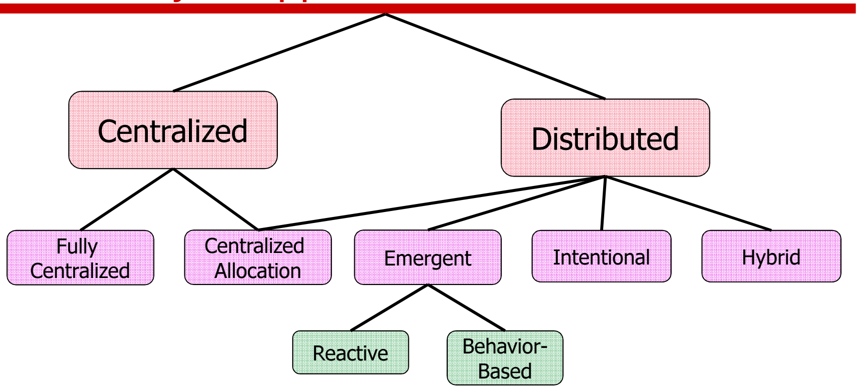
Interference

- Robots can interfere with each other at different levels
  - physical interference
    - competition for physical resources, like space
  - task interference
    - competition for task resources, like objects
    - competition for winning resources, like goals, pieces, etc.

Control Approaches

- How can we control a group of robots?
- Two basic options exist:
  - centralized control
  - distributed control
- Between these two ends of the control spectrum, there are numerous compromises, in the form of hierarchical control

Taxonomy of Approaches



The Coordination Spectrum

Loosely-Coordinated

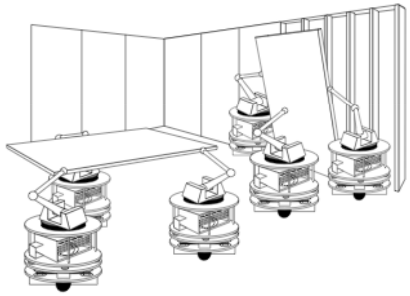
- Decomposable into subtasks
- Independent execution
- Minimum interaction
- Task decomposition and allocation strategies.

Tightly Coordinated

- Tasks not decomposable
- Coordinated execution
- Significant Interaction

Fully Centralized

- Single agent plans for entire team
- ✚ Potential to be optimal
- ✚ Implicitly encodes coordination
- – Usually computationally intractible
- – Single point of failure
- – Slow to respond to changes

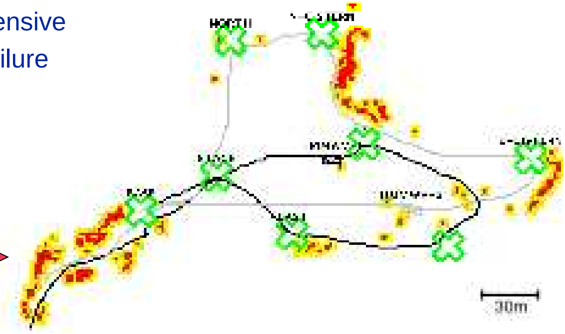


Centralized construction;
Khatib et al 1996

Centralized Allocation

- Single agent assigns tasks to teammates
- Teammates complete tasks individually
- ✚ Execution is distributed
- ✚ Allocation can be optimal
- – Still computationally expensive
- – Still has single point of failure

GRAMMPS
Brummitt and Stentz; 1996



Reactive

- Robots have a tight sense-act loop
- ✚ Extremely fast
- ✚ Very simple
- – Cannot handle comple: tasks

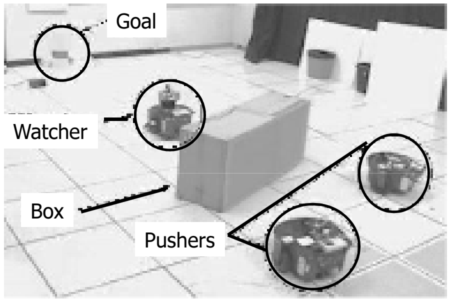
Caloud et al; 1990

Behavior-based

- Use state information to choose actions
- ✚ Fast, simple
- ✚ Robots can contribute to multiple tasks
- ✚ More expressive than reactive
- — Still cannot plan

Intentional

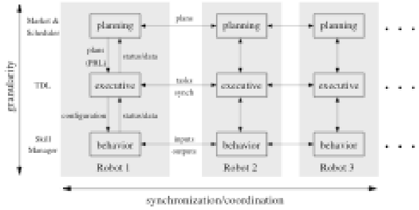
- Communication with the intent to coordinate
- ✚ Facilitates planning, scheduling
- ✚ Better solutions
- – Slow in time-critical situations
- – Very dependent on communication



MURDOCH; Gerkey and Mataric

Hybrid

- Emergent approach in larger intentional approach
- ✚ Allows better planning/distribution of resources
- ✚ Can have tight coordination
- – Cannot have complex interactions



Trestle; Simmons et al

Loosely Coordinated Teams

- Behavior-based
- Central Task Allocation
- Intentional - Market Systems

Tightly-Coordinated Teams

- Fully centralized
- Reactive

Example Taxonomy

- Team size
- Communication range
- Communication topology
- Communication bandwidth
- Team reconfigurability
- Team unit processing ability
- Team composition

Dudek/Jenkin/Milios/Wilkes taxonomy: SIZE

- SIZE: The number of robots in the environment.
  - ALONE: one robot
  - PAIR: two robots
  - LIM (limited group of robots)
  - INF (infinite group of robots))

Dudek/Jenkin/Milios/Wilkes taxonomy: COM

- COM: Communication range.
  - NONE: no direct communication
  - NEAR: only robots within a short distance can be communication with directly
  - INF: no limit to the robots' direct communication capabilities

Dudek/Jenkin/Milios/Wilkes taxonomy: TOP

- TOP: Communication topology
  - BROAD: Broadcast; all information is sent and received by all robots within range
  - ADD: Address; direct messaging is allowed on a named (addressed) basis
  - TREE: only hierarchical communication is allowed
  - GRAPH: arbitrary communication pathways can be established

Dudek/Jenkin/Milios/Wilkes taxonomy: BAND

- BAND: Bandwidth of the communication
  - ZERO: no communication is available
  - LOW: communication costs are very expensive
  - HIGH: communication is free
  - MOTION: the cost of motion between two points is free
  - BAND-MOTION: motion and communication costs are approximately the same

Dudek/Jenkin/Milios/Wilkes taxonomy: ARR

- ARR: Rearrangement; the rate at which the collective can spatially re-organize itself; team reconfigurability.
  - STATIC: no changes are permitted
  - COMM: communication coordinated; the team members coordinate rearrangement/reconfiguration using communications
  - DYN: dynamic; arbitrary reorganization is permitted

Dudek/Jenkin/Milios/Wilkes taxonomy: PROC

- PROC: The processing ability of individuals in the collective
  - SUM: non-linear summation
  - FSA: finite-state-automata
  - PDA: push-down-automata
  - TME: Turing machine equivalent

Dudek/Jenkin/Milios/Wilkes taxonomy: CMP

- CMP: Team composition.
  - HOM: Homogenous; all agents are the same
  - HET: Heterogeneous; there are more than one type within agents

Examples using the Dudek/Jenkin/Milios/Wilkes taxonomy:

- Bees:
  - SIZE-INF, COM-NEAR, TOP-BROAD, BAND-MOTION, ARR-DYN, PROC-TME, CMP-HET
- Combat aircraft:
  - SIZE-LIM, COM-LONG, TOP-BROAD, BAND-INF, ARR-DYN, PROC-TME, CMP-HET
- Automobile:
  - SIZE-LIM, COM-NEAR, TOP-BROAD, BAND-MOTION, ARR- D?N, PROC-TME, CMP-HET
- Box-pushing robot team:
  - SIZE-PAIR, COM-NEAR, TOP-ADD, BAND-INF, ARR-STATIC, PROC-TME, CMP-HOMM

Multi-Robot Task Allocation Taxonomy

- Gerkey-Mataric [2004]
  - Single-task robots (ST) vs. multi-task robots (MT):
  - Single-robot tasks (SR) vs. multi-robot tasks (MR):
  - Instantaneous assignment (IA) vs. time-extended assignment (TA)

Single-task robots vs. multi-task robots

- ST means that each robot is capable of executing at most one task at a time
- MT means that some robots can execute multiple tasks simultaneously.

Single-robot tasks vs. multi-robot tasks

- SR means that each task requires exactly one robot to achieve it
- MR means that some tasks can require multiple robots.

Instantaneous assignment vs. time-extended assignment

- IA means that the available information concerning the robots, the tasks, and the environment permits only an instantaneous allocation of tasks to robots, with no planning for future allocations.
- TA means that more information is available, such as the set of all tasks that will need to be assigned, or a model of how tasks are expected to arrive over time.

ST-SR-IA: Single-task robots, single robot tasks, instantaneous assignment

- Simplest problem.
- An instance of the Optimal Assignment Problem (OAP) (Gale 1960)
- Well-known problem that was originally studied in game theory and then in operations research, in the context of personnel assignment.

ST-SR-TA: Single-task robots, single robot tasks, time-extended assignment

- When the system consists of more tasks than robots, or if there is a model of how tasks will arrive, then the robots' *future* utilities for the tasks can be predicted with some accuracy, and the problem is an instance of ST-SR-TA.
- This problem is one of building a time-extended *schedule* of tasks for each robot, with the goal of minimizing total weighted cost.

ST-MR-IA: Single-task robots, multirobot tasks, instantaneous assignment

- Problems that involve tasks that require the combined effort of multiple robots.
- The *combined* utilities of groups of robots, which are in general *not* sums over individual utilities must be considered.
- Utility may be defined arbitrarily for each potential group.
  - For example,if a task requires a particular skill or device, then any group of robots without that skill or device has zero utility with respect to that task, regardless of the capabilities of the other robots in the group.
- This kind of problem is significantly more difficult
- In the multi-agent community, referred to as *coalition formation*, and has been extensively studied

ST-MR-TA: Single-task robots, multirobot tasks, time-extended assignment

- Includes both coalition formation and scheduling.

MT-SR-IA & MT-SR-TA: Multi-task robots, single-robot tasks

- Currently uncommon due to small number of actuators on robots

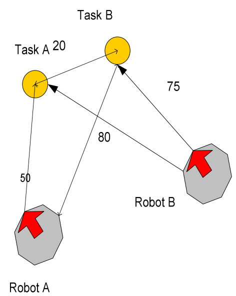
MT-MR-IA: Multi-task robots, multirobot tasks, instantaneous assignment

- system consists of both multi-task robots and multi-robot tasks.

MT-MR-TA: Multi-task robots, multirobot tasks, time-extended assignment

- An instance of a scheduling problem with multiprocessor tasks and multipurpose machines.

Market Based Task allocation in Robot Soccer



Costs

$$C_{ES} = \mu_1 . t_{dist} + \mu_2 . t_{align} + \mu_3 . clear_{goal}$$

$$C_{bidder} = \mu_4 . t_{dist} + \mu_5 . t_{align} + \mu_6 . clear_{teammate(i)} + C_{ES(i)}, i \neq robotid$$

$$C_{auctionerr} = C_{ES(robotid)}$$

$$C_{defender} = \mu_7 . t_{dist} + \mu_8 . t_{align} + \mu_9 . clear_{defense}$$

Task Assignment