Multi-Robot Systems

- Prepared by:
  - Lynne E. Parker, Univ. of Tennessee (UT)
  - Maja J. Matarić, Univ. of Southern California (USC)
  - Manuela Veloso, Carnegie Mellon Univ. (CMU)
  - Tucker Balch, Georgia Institute of Technology (GaTech)

Multi-Robot Systems: Description and Major Subtopics

- Description:
  - This topic concerns teams of 2 or more autonomous mobile robots.
- Major Subtopics:
  - Task Allocation/Action Selection/Coordination/Control Architectures
  - Object Transport, Manipulation, Construction
  - Communication and Perception
  - Motion Coordination
  - Learning
  - Reconfigurable/Modular/MEMS robotics
  - Localization/Mapping

Major Laboratories and Investigators
(all with current active research)

- USC Center for Robotics and Embedded Systems – Maja Matarić, Gaurav Sukhatme, Wei-Min Shen, Andrew Howard
  - Control and learning, task allocation, mobility and coordination, ground + aerial vehicles, reconfigurable robots, multi-robot localization, mapping, and exploration, sensor net deployment
- CMU Robotics Institute – Manuela Veloso, Reid Simmons, Tony Stentz, Bernardine Dias
  - Adversarial environments, soccer, planning, coordination, learning, distributed perception, human-robot partnering, distributed robot architectures, heterogeneous task allocation, construction, market-based methods

Major Laboratories and Investigators (Con't.)

(all with current active research)

- UT Distributed Intelligence Lab – Lynne Parker
  - Heterogeneous teaming, adaptation and learning, motivation-based task allocation, distributed sensor sharing, mobile sensor net deployment, large-scale heterogeneous teams, fault-tolerant systems, distributed motion control

- GaTech Mobile Robot Lab and Borg Lab – Ron Arkin, Tucker Balch
  - Collaborative perception, modeling and tracking, soccer, social animal behavior, social potentials for cooperative behavior, metrics for team diversity, mission planning, military applications, multi-level learning

Major Laboratories and Investigators (Con't.)

(all with current active research)

- UPenn GRASP Lab – Vijay Kumar
  - Control-theoretic formation control, aerial + ground vehicles, distributed perception and situation awareness, cooperative localization

- MIT – Daniela Rus
  - Self-reconfigurable modular robots, distributed manipulation

James McLurkin (iRobot)

  - Swarm behaviors

Major Theoretical Accomplishments

- Task Allocation/Action Selection/Coordination/Control Architectures:
  - Matarić's basis behaviors showed how more complex cooperative behaviors can be built from simpler behaviors.
  - Parker's ALLIANCE architecture for task allocation showed how inter-robot coordination can be achieved via motivations, without negotiation.
  - Balch's social entropy metric enables quantitative measure of heterogeneity.
  - Balch & Stroupe developed value-based navigation to maximize team performance.
  - Gerkey & Matarić showed that multi-robot coordination can be cast as multi-robot task allocation (MRTA).
  - Jones & Matarić developed methods for automated generation of provably satisficing algorithms for multi-robot coordination.
  - Dias developed understanding of how market-based methods can be used for successful multi-robot coordination.
  - Veloso, *et al.* developed skills-tactics-plays architecture.
  - Veloso, *et al. d*eveloped greedy role assignment and gradient-based positioning.
- Object Transport, Manipulation, Construction:
  - Latombe *et al.* developed tightly-coupled object transport.
  - Huntsberger, *et al.*, developed tightly-coupled object transport in rough terrain.

Major Theoretical Accomplishments (con't.)

- Communication and Perception
  - Balch and Arkin showed how minimal amounts of communication can lead to significantly more efficient cooperative behaviors.
  - Veloso, *et al*. developed dual model for fusion of distributed information
- Motion Coordination
  - Balch and Arkin developed comparative analysis of alternative formations
  - Parker developed distributed solution to multi-robot tracking task (CMOMMT)
  - Kumar, *et al.,* developed control-theoretic formation control
  - Matarić developed leaderless adaptive formations
  - Jun and Sukhatme developed target- and robot-density-based coordination for multi-robot tracking

Major Theoretical Accomplishments (con't.)

- Learning
  - Veloso, *et al.* developed variable-learning-rate reinforcement learning in multi-robot teams, and for adversarial environments
- Reconfigurable/modular/nano-robotics
  - Rus developed generic distributed self-reconfiguration planner with provable correctness and instantiations to 3 different robots
  - Shen developed control techniques for modular robot systems
  - Yim developed distributed control techniques for modular robot systems
- Localization/Mapping
  - Howard, *et al.* demonstrated large-scale mapping based on incremental SLAM, cooperative localization, and manifold mapping
  - Konolige, Fox, *et al.,* demonstrated large-scale cooperative mapping

Major Practical Embodiments

- Matarić demonstrated 13 mobile robots performing coordinated movement (flocking, foraging, following, etc.)
- Parker demonstrated significant fault tolerance in heterogeneous multi-robot teams
- Parker and Matarić (separately) demonstrated heterogeneous multi-robot box pushing
- Kube demonstrated homogeneous (swarm-type) box pushing
- Matarić demonstrated automated construction (wall-building)
- Veloso and Balch (and others) have demonstrated successful robot soccer teams on multiple types of platforms
- Yim demonstrated Polybot reconfigurable robot
- Rus demonstrated the Molecule self-reconfiguring robot (3d self-reconfiguration)
- Castano demonstrated CONRO reconfigurable robot
- Khosla, *et al.,* demonstrated Millibots for cooperative mapping and exploration
- Univ. Minnesota demonstrated SCOUT robots for data-gathering tasks
- Saripalli, *et al.,* demonstrated cooperative air- and ground-vehicle cooperation
- Howard, Parker, and Sukhatme demonstrated large-scale (35-100) heterogeneous teams performing indoor localization, mapping, object detection, and surveillance
- Konolige, Fox, *et al*. demonstrated large-scale (35-100) robot teams performing indoor localization, mapping, object detection, and surveillance
- McLurkin*, et al.,* demonstrated swarm behaviors on large number (50?) of physical robots

Influential Papers (incomplete)

- Fukuda, CEBOT research, 1988.
- Balch, Arkin, "Communication in Reactive Multiagent Robotic Systems", *Autonomous Robots*, 1995.
- Dudek, Jenkin, Milios, Wilkes, "A Taxonomy for Multi-Agent Robotics", *Autonomous Robots*, 1996.
- Cao, Fukunaga, and Kahng, "Cooperative Mobile Robotics: Antecedents and Directions", *Autonomous Robots,* 1997.
- Mataric, "Behavior-Based Control: Examples from Navigation, Learning, and Group Behavior"*, J. of Experimental and Theoretical Artificial Intelligence,* 1997.
- Parker, "ALLIANCE: An Architecture for Fault Tolerant Multi-Robot Cooperation", *IEEE Transactions on Robotics,* 1998.
- Veloso, "Autonomous Robot Soccer Teams", *The Bridge*, National Academy of Sciences, 2003.
- ...

Also, many workshops, special journal issues, tutorials, etc.

Major Unsolved Problems and Challenges

- Task Allocation/Action Selection/Coordination/Control Architectures
  - Designing heterogeneous systems and techniques for automatically generating provably correct adaptive distributed planning and control algorithms.
  - Finding effective on-line solutions, i.e., approximation algorithms to the remaining task allocation problems which are formally known to be NP-complete.
  - Incorporating aerial dynamics into planning for joint tasks.
  - Achieving efficient use of heterogeneous multi-robot teams for highly complex tasks.
  - Achieving successful operation of human-robot teams and successful optimization of operator-preferences in multirobot task executions.
  - Generating fast and effective team decision making (for parallel and/or sequential tasks).
  - Development of passive action recognition capabilities.
- Object Transport, Manipulation, Construction
  - Increasing complexity and difficulty of transport, manipulation, and construction tasks, especially over rough terrains.
- Communication and Perception
  - Modeling and incorporating realistic communication models into control.
  - Achieving robust multi-robot perception; real-time fusion of single robot information and communicated information.
  - Robust handling of error-prone communications environments.

Major Unsolved Problems and Challenges (con't.)

- Motion coordination
  - Proving stability of the region-based tracking approach.
  - Studying the scaling properties of the region-based tracking approach.
- Learning
  - Developing effective on-line multi-robot learning algorithms.
  - Achieving creative adaptation to dynamic conditions.
  - Learning teamwork through experience.
  - Dealing with team credit-blame assignment.
  - Understanding impact of heterogeneous capabilities towards optimal team performance.
- Reconfigurable/modular/MEMS-robotics
  - Demonstrating techniques in practical applications.

Research Goals Benefiting from Substantial New U.S. Funding

- Addressing issues of scalability / System of systems
  - From 10's to 100's and 1000's
  - Networked control
  - Communication for control and perception
  - Combining prior information (deliberative control) with dynamic information (reactive control)
- Generation of a set of benchmark testbeds available to all; a set of tasks to be accomplished by different robot and human-robot teams, including criteria for success.
- Funding of projects that will be extensively tested on physical robots – not just in simulation.

Research Goals Benefiting from Substantial New U.S. Funding (con't.)

- Team operations in real-world complex problem domains (such as construction), and/or adversarial environments.
- Achieving greater robustness and dynamic team reorganization based on partial system failures.
- Finding effective on-line solutions to difficult learning and/or task allocation problems.

Major Accomplishments in Other Countries/Profitable Collaborations

- Marco Dorigo, Brussels
  - SWARM-BOT: Artificial Life, swarm robotics, small-scale robots.
- Rachid Alami, INRIA, France
  - Multi-robot planning and coordination; MARTHA project for container delivery/coordination/storage in shipping ports
- Hajime Asama, RIKEN/Univ. Tokyo, Japan
  - Intelligent data carriers for distributed communications through space/time