Biomimetic Coordination and Cooperation of Multiple Rovers

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Since 1990, we have been working on coordination of multiple mobile robots, using distributed, low-computation, local methods. This work was initiated at MIT, and is not being continued at USC. The continuing goal of this work has been to take themes from biology, including decentralized, distributed control based on individual, local sensing and limited computation, and apply them to engineering domains such as distributed exploration and cooperation, with applications in space exploration, as well as Earth de-mining, toxic spill cleanup, agriculture, etc. Our work is demonstrated and evaluated on groups of physical mobile robots with on-board power, computation, and sensing.

The biological motivation of our work is particularly relevant, because multi-robot control is not well handled with standard, centralized approaches, which require a bottleneck controller to acquire complete sensory and state information of all individuals in order to plan their actions. Such solutions have been demonstrated to be intractable for groups larger than two or three robots, when the robots are placed in real-world environments even as simple as robotics laboratories, not to mention other planets and asteroids.

Our work has focused on developing robust, reliable, and repeatable strategies for using local control of individual robots which results in coherent and efficient global behavior of the group. Our experiments have robustly demonstrated the largest coordinated real-robot behaviors to date, with groups of 13 robots displaying movement in formation (flocking, following, homing, herding), and were the first to demonstrate such large-group coordination of physical mobile robots.

Our more recent work has demonstrated multi-agent and robot distributed mapping, adaptive task division, movement in formation, space coverage, and multi-robot adaptation and learning in complex, noisy, and non-stationary domains. The agents and robots are able to learn, in real time, using simple on-board processing, to behave more optimally relative to the others. Importantly, this adaptation happens on a short time-scale (on the order of 10-15 minutes, rather than the usual hours required for machine learning techniques) and thus enables equally fast adjustment of the individual and group behavior as the dynamics of the task change over time.

This work finds its basis deeply rooted in principles and data from neuroscience and ethology. The former provides constraints on the organization of behaviors as underlying structures for control (such as those found in the motor control system, which may serve to reduce the high dimensionality of the problem), while the latter provides examples of group behaviors with stable dynamics (ranging from small groups of animals to large hierarchical human organizations). In all cases, the control is located within the individual, and based on distributed, low-computation, local methods, consisting of networks of interacting behaviors. For example, in the case of a mobile robot, the underlying behavior substrate may be a basis set of avoid, aggregate, disperse, follow, communicate, listen, and the resulting group behavior can produce high complex and adaptive group structures resulting from the interaction dynamics within the agents' behavior system (i.e., from activation and inhibition influences among behaviors), and among the agents in the environment. Importantly, our work focuses on control strategies, and not on locomotion mechanisms, so it can be applied to a variety of rover types. In fact, our work is currently being applied to legged, tracked, and underwater vehicles. Since the original motivation for our work comes from space applications, we are particularly eager to get involved in a discussion of applying these biologically-inspired behavior-based control methods to that domain.

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http://www-robotics.usc.edu/

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Issues in Coordinated Behavior

- Locomotion
- Power
- Sensing
- Communication
- Coordination and Cooperation
- Adaptation & Learning

IRs
contact
Sonar
color vision
radios

26+ mobile robots (heterogeneous)

IS ROBOTICS + REAL WORLD INTERFACE

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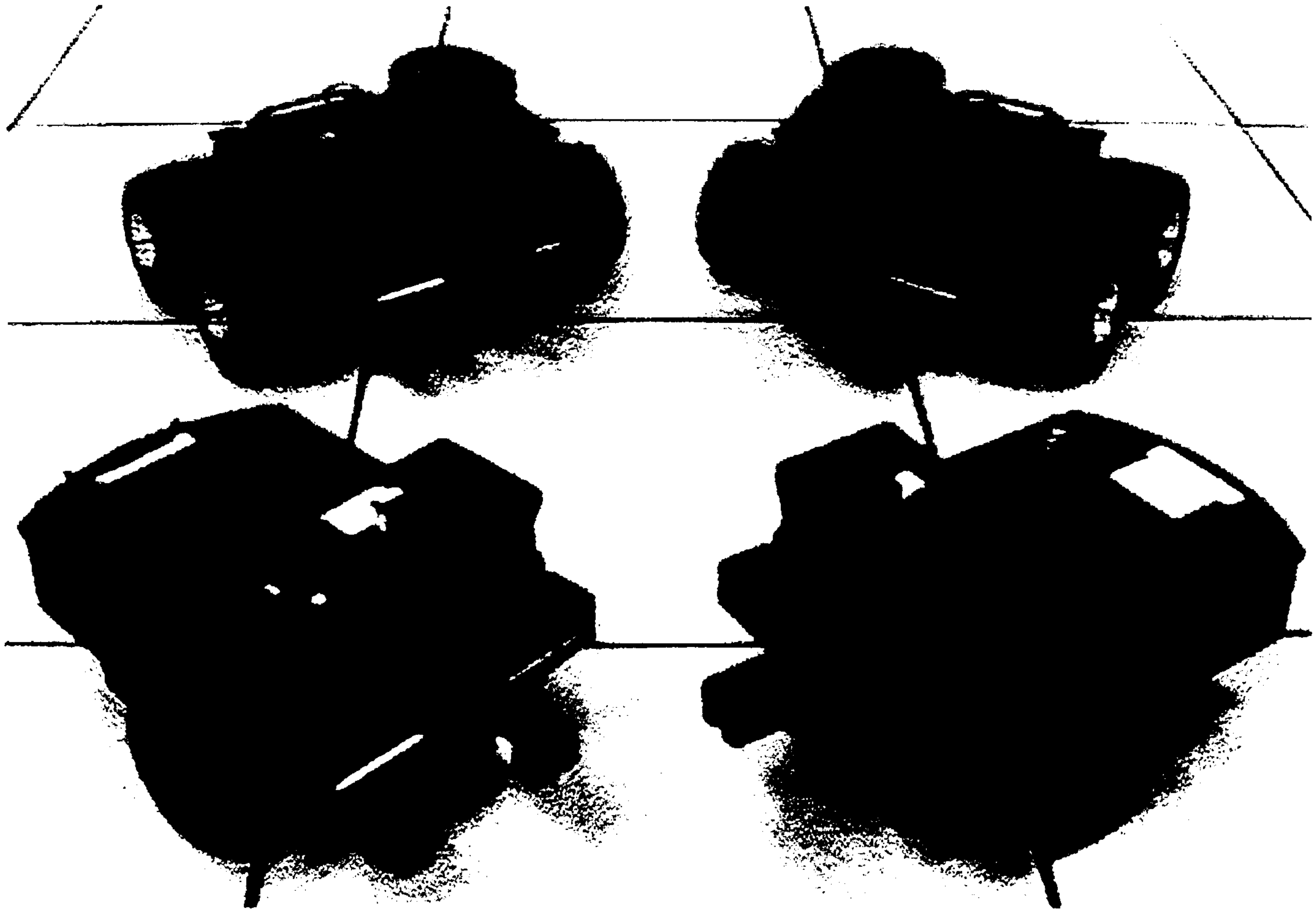
RWI Pioneer Robots



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K-Team Khepera Robots

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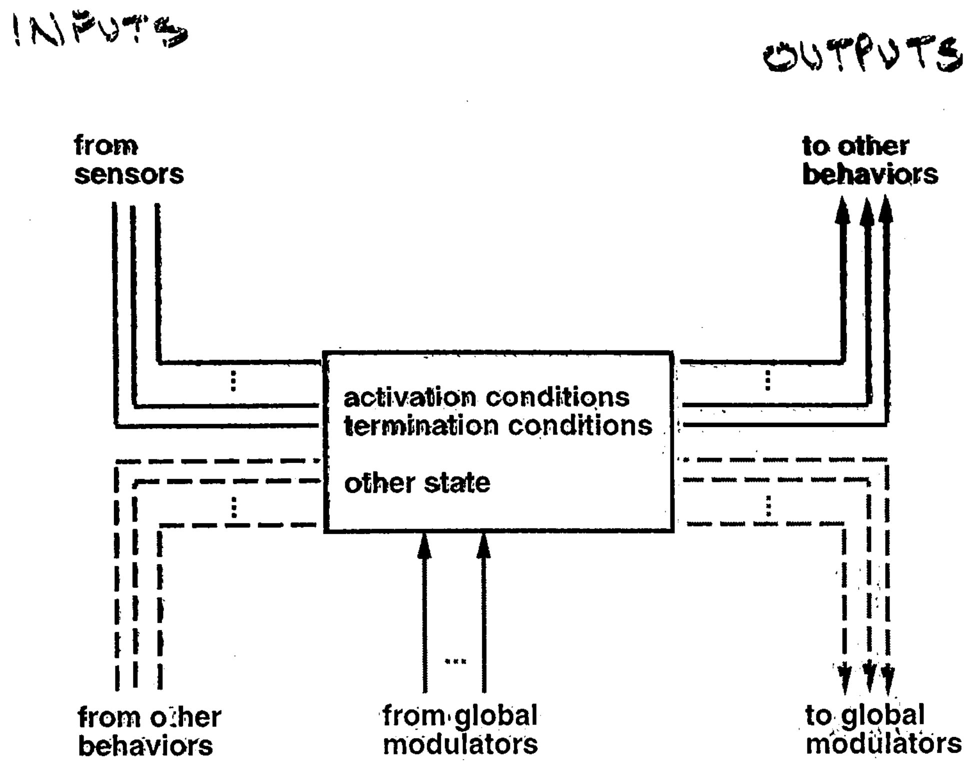
The Basis Behavior Approach

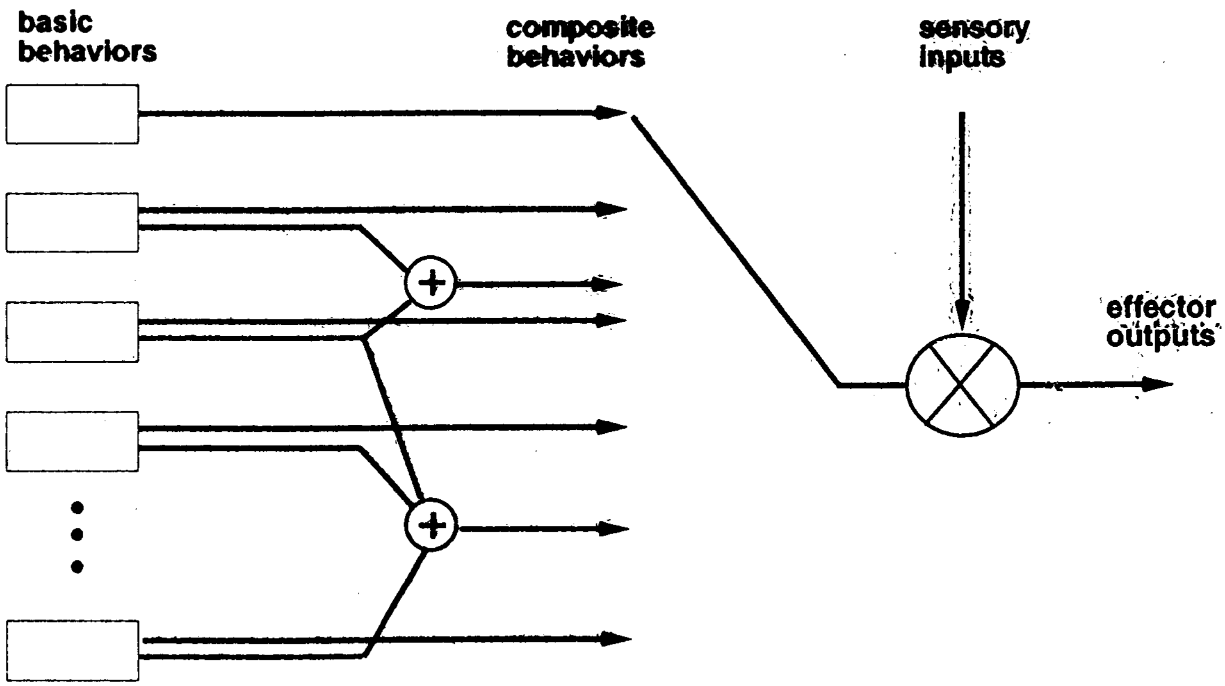
- Use well-defined *behaviors* as primitives for:
  - control, representation, and learning
- Behaviors:
  - are goal-driven control laws
  - exploit the system dynamics
  - achieve and/or maintain goals
- A small basis set of behaviors is:
  - hand-coded, learned, or evolved
  - used as a substrate for higher-level behaviors

BEHAVIOR STRUCTURE

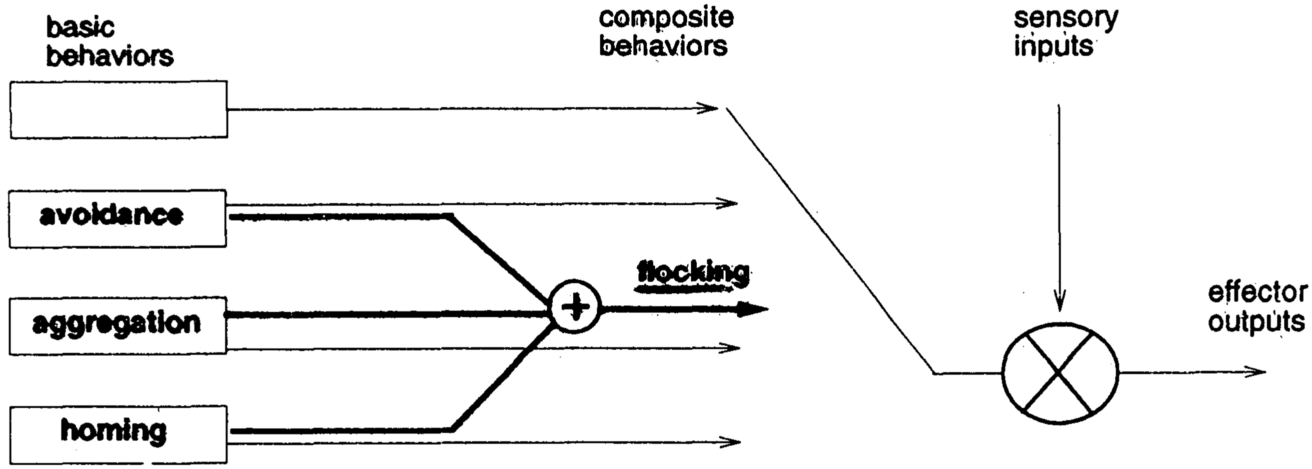


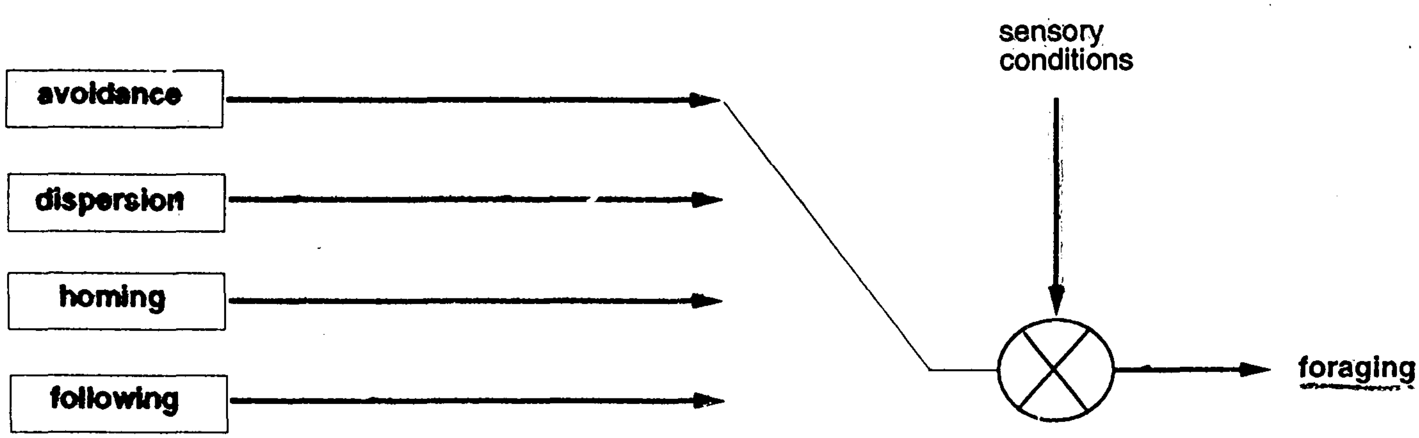
Combining Basic Behaviors

- temporal overlap – summing
- temporal exclusion – switching



Examples of Combining Basic Behaviors





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Strengths of the Approach

- Behavior-based control has proven to be:
  - robust
  - reactive
  - extensible
  - low-computational overhead
- The basis behavior approach is:
  - biologically inspired and motivated
  - principled
  - scaleable (through combination operators)

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Demonstrations to Date

- Large-scale (<= 14) multi-*robot* coordination
- A range of robot sizes
  - Kheperas (1.5" x 2") to Pioneers (24" x 12")
- Homogeneous and heterogeneous groups
- Different types of locomotion
  - 2 wheels, 4 wheels, tracks, helicopters, 6 legs
- A broad range of tasks
- Adaptive and learning capabilities

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Collective Tasks

- Coordinated movement
  - loose coordination: following, flocking, chaining, homing, dispersion, aggregation
  - tight coordination: formations, object pushing/moving
- Distributed mapping
  - indoor, outdoor
- Distributed collection
  - foraging, de-mining, sample return
- Robot soccer

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Adaptation & Learning

- Distributed map learning
- Learning to collect/forage in a group
- Cooperative object pushing/moving
- Learning social rules (e.g., yield, communicate)
- On-line group reconfiguration (e.g., territories)
- On-line dynamic task division
- New task learning by imitation

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The Learning Approach

- On-line and in real-time (minutes)
- Using the behavior substrate
  - behavior selection, combination, new behaviors
- Low-overhead methods
  - statistics and adapted reinforcement learning
  - elevated representational substrate (behaviors, networks)
  - exploiting *a priori* structure and bias (not tabula raza)

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The Learning Approach, cont.

- Fast adaptation to changing environments
  - dealing with nonstationarity
  - capturing dynamics in real time
- Utilizing multiple robots
  - communication for handling credit assignment and hidden state (due to sensor limitations and noise)
- Imitation and social learning
  - positive feedback (recruitment)
  - skill and goal transfer

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Enabling Technologies

- Sensors
  - smaller, cheaper, more ubiquitous tactile & vision
- "Social" sensors
  - who is the other guy, where is (an)other guy, etc.
- Power for locomotion (not computation)
- Communication
- Miniturization for scalability
  - for critical mass, emergent behavior studies

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Key Properties/Strengths

- Low computational overhead
- Physical and computational robustness
- Scalability
- Generality/reusability of basic behaviors
- Reconfigurability
- Adaptivity
- Full autonomy
- Commandability