Multiagent Control of Modular Self-Reconfigurable Robots

Tad Hogg
HP Labs

Hristo Bojinov
Jeremy Kubica
Arancha Casal
PARC’s modular robotics group
topics

- modular robots
- multi-agent control
- results
modular robots

- collections of modules
  - each module is a robot
- self-reconfigurable
  - modules can change connections
  - so overall robot changes shape
- “modular self-reconfigurable” robots
  - MSR
why change shape?

• adjust shape to task
• e.g., locomotion
  - wheel, spider, snake, ...
• e.g., manipulation
  - match “finger” size to object size
topics

• modular robots
  - Proteo
  - Prismatic
  - future possibilities
• multi-agent control
• results
Proteo

• rhombic dodecahedron
• space filling
Proteo

- modules move over neighbors

each edge of cube is a diagonal of RD face
topics

• modular robots
  - Proteo
  - Prismatic
  - future possibilities
• multi-agent control
• results
prismatic MSR robots

• modules connect via arms
• extending arms moves neighbors
• examples
  - Crystalline robot (Dartmouth)
    • moves in 2 dimensions
  - TeleCube (PARC)
    • moves in 3 dimensions
TeleCube

- cubes
- 6 independent arms
- 2:1 length ratio
neighbors cooperate to move

physical move

contract

expand

virtual move
topics

- modular robots
  - Proteo
  - Prismatic
- future possibilities
- multi-agent control
- results
devices for “smart matter”

- micro-electromechanical (MEMS)
- bacteria
- molecular
- quantum

sensor + computer + actuator
micromachines (MEMS)

- made with photolithography
  - e.g., programmable force fields (open loop)
- hard to assemble
biological machines

• biotechnology: program bacteria
  - e.g., T. Knight, R. Weiss at MIT AI Lab
• limited abilities
programs for bacteria

• gene regulatory networks
• engineered changes give some program control over behavior
molecular machines

• ribosomes:
  - make proteins in cells

• protein motors
  - move material in cells
  - ATP synthase rotor
    - size: 10nm

molecular machines

• carbon nanotubes and buckyballs
  - strong, light, flexible, electronic devices
  - easy to make
  - hard to arrange
molecular machines

• complex molecules for robot parts
• currently:
  - only theory
  - hard to make
  - hard to assemble
• potential: cheap, fast, strong parts

example designs:
E. Drexler, R. Merkle, A. Globus

example medical applications:
R. Freitas, Jr., Nanomedicine, 1999
quantum computers

- potential: much faster algorithms
  - e.g., factoring
- very difficult to build

quantum search heuristic

quantum machines

• potential: detail control over materials
  - e.g., interfere two ways to absorb light => transparent

• very difficult to build

See T. Hogg and G. Chase, Quantum smart matter, 1996

S. Lloyd and L. Viola, Control of open quantum systems dynamics, 2000
quantum machines

- example: coin weighing puzzle
  - quantum sensor finds bad coin in single try

devices: summary

• smaller devices
  - harder to make
  - harder to connect, assemble
  - greater potential capability
• but need many, cheap devices
• statistical or systems view
challenge: How to build?

• physical/engineering constraints
  - unreliable parts
  - misconnected
• limits early technology
• economics
  - build cheaply
challenge: How to use?

• information/computational constraints
  - limited, changing info from environment
  - computational complexity
    • e.g., planning optimal device use

• limits even mature technology
topics

- modular robots
- multi-agent control
- results
control challenge

- coordinate many modules
- sensor & actuator errors
- decompose programming task to only need
  - local info (small scale)
  - high-level task description (large scale)
    - e.g., grasp object of unspecified shape

cf., H. Simon: nearly decomposable systems
control before hardware?

• many, small modules don’t yet exist
  - hence, hardware details unknown
  - but can study general issues
• control may simplify hardware design
  - e.g., manage in spite of defects
  - identify compute/communicate tradeoffs

sensor + computer + actuator
physics vs. size

- gravity
- friction
- Brownian motion
- thermal noise
- decoherence
- MEMS
- molecular
- quantum

faster
smaller
harder to build
multi-agent control

• matches control to physics
  - different agents for each scale

• matches control to available info
  - rapid response to local info
  - manager agents: overall coordination
    • without need for details
motivation: biology

social insects, multicellular organisms, ecology
reliable behavior from unreliable parts

examples
termite mounds
embryo growth

cf. incentive issues
noncooperative agents
economics, common law, ...
motivation: teams

- robot soccer
- insect-like robot teams
  - e.g., foraging
- MSR robots have
  - tighter physical constraints
  - direct access to neighbor locations
    - e.g., no need for vision to find neighbors
topics

- modular robots
- multi-agent control
- results
  - computational ecology
    - Proteo
    - Telecube
computational ecology

• dynamical behavior of simple agents
  - asynchronous, local decisions
  - delays, imperfect information
  - “mean-field” statistical theory

• apply to actual robot behaviors
  - see K. Lerman et al. in *Artificial Life*, 2001
techniques

• finite-state machine for each module
  - simple script, some randomness
• local communication
  - create gradients through structure
  • “scents”
topics

- modular robots
- multi-agent control
- results
  - computational ecology
  - Proteo
  - Telecube
example: growing a chain

• modes:
  - SLEEP, SEARCH(red), SEED(yellow), FINAL(white)
  - initially: all in SLEEP, randomly pick one SEED

• seed:
  - picks growth direction
  - emits scent
    • attracts modules
growing a chain

descend gradient + propagate scent

if neighbor is seed

emit scent=0

if neighbor became seed
- set $S = \min(\text{neighbors}) + 1$
- move around neighbor until lower value found
- if seed found: become new seed
structures

- recursive branching
  - multilevel arms
- grow around object
  - using contact sensors

See H. Bojinov et al., Multiagent Control of Self-reconfigurable Robots, 2000
www.arxiv.org/abs/cs.RO/0006030
topics

- modular robots
- multi-agent control
- results
  - computational ecology
  - Proteo
  - Telecube
locomotion

- make snake shape
- move toward goal
  - barrier
    - follow wall
    - find gap

- higher-level control: general direction
  - building on low-level agent behavior

see: Kubica et al, Proc. ICRA 2001
object manipulation

• exert forces to move object
  - based on contact with object
  - “scent” recruits other modules

• modules on surface form rigid shell
summary

• simple agents perform basic tasks
  - reconfiguration
  - locomotion
  - manipulate objects

• apply to different hardware types
  - Proteo: surface motions
  - TeleCube: internal motions
future directions

- quantify capabilities
- design more complex behaviors
- implement on hardware
quantify capabilities

- examples of agent-based control
  - are only specific instances
- quantify
  - how robust?
  - how accurate?
  - what cost?
  - e.g., power use
agent design

• combine with higher-level agents
  - e.g., switch among low-level behaviors

• automate agent design
  - e.g., genetic algorithms (FXPAL)
test on hardware

• various existing robots
  - few, fairly large modules

• large number of tiny modules
  - don’t yet exist

• wait for hardware vs. simulate?
  - understand likely hardware capabilities
  - e.g., MEMS, …
conclusions

• agent-based control for MSR robots
  - gives robust low-level behaviors
  - simplifies higher-level task control

• biological system models
  - suggest module rules
  - useful even if not biologically accurate

www.hpl.hp.com/shl/people/tad