mc375: intro to robotics

behavior-based systems.

- control
- behavior-based systems
- expressing behaviors
- behavioral encoding
- representations
- example: Toto
- behavior coordination
- emergent behavior

control:

models.

we like to make a distinction between

- classic “model-based” AI
  - symbolic representations
- neo “behavior-based” AI
  - numeric representations

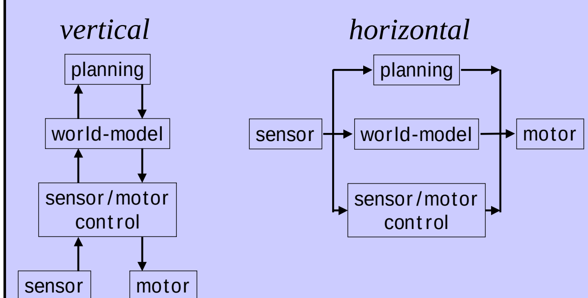
control:

classic models.

- deliberative… SPA (sense,plan,act)
  - functional decomposition
    - systems consist of sequential modules achieving independent functions
      - sense world
      - generate plan
      - translate plan into actions
- reactive architectures
  - task-oriented decomposition
    - systems consist of concurrently executed modules achieving specific tasks
      - avoid obstacle
      - follow wall

control:

two orthogonal flows.



control:

distinctions.

- key issues that distinguish architectures
  - time scale
  - looking ahead
  - modularity
    - the way in which the architecture decomposes into components

control:

behavior-based systems.

- BBS
- behaviors are the underlying module of the system
- behavioral decomposition
  - systems consist of sequential modules achieving independent functions

control:

robotic behavior.

- generate a motor response from a given perceptual stimulus
- basis in biological studies
  - serves as inspiration for design

control:

behavior vs action.

- behavior
  - based on dynamic process
    - operating in parallel
    - lack of a central control
    - fast couplings between sensors and motors
  - exploiting emergence
    - side-effects from combined processes
    - using properties of the environment
  - reactive
- action
  - discrete in time
    - well-defined start and end points
    - allows pre- and post-conditions
  - avoidance of side-effects
    - only one action or few actions at a time
    - conflicts are undesired and avoided
  - deliberative

behavior-based systems:

...are reactive systems.

- behaviors serve as building blocks for actions
- abstract representation avoided
- often modeled after animal behaviors
- inherently modular

behavior-based systems:

stimuli.

- presence of stimulus is necessary but not sufficient in behavior-based robot
- stimulus must reach threshold value before response is generated

behavior-based systems:

representation.

- behaviors can be represented/stored in a network, with relationships between them
- strength multiplier, or gain, can turn off behaviors or increase response

behavior-based systems:

properties.

- feedback controllers
- achieve specific tasks/goals
  - avoid others, find friend, go home
- typically execute concurrently
- can store state and be used to construct world models/representations
- can directly connect sensors to effectors
- can take inputs from other behaviors and send outputs to other behaviors (⇒ networks)

behavior-based systems:

properties, 2.

- typically higher-level than actions (go home, not turn left 45º)
- typically closed loop, but extended in time
- when assembled into distributed representations, behaviors can be used to look ahead but at a time-scale comparable with the rest of the system

behavior-based systems:

key properties.

- ability to act in real time
- ability to use representations to generate efficient (not only reactive) behavior
- ability to use a uniform structure and representation throughout the system (so no intermediate layer)

behavior-based systems:

key challenge.

- how can representation be effectively *distributed* over the behavior structure?
  - time scale must be similar to that of real-time components of the system
  - representation must use same underlying behavior structure for all components of the system

behavior-based systems:

challenges, 2.

- some components may be reactive
- not every component is involved with representational computation
- some systems use a simple representation
- as long as the basis is in behaviors and not rules, the system is a BBS

behavior-based systems:

what are behaviors?

- *behavior:* anything observable that the system/robot does
- how do we distinguish internal behaviors (components of a BBS) and externally observable behaviors?
- should we distinguish?

behavior-based systems:

external vs internal.

- reactive robots display desired external behaviors
  - avoiding
  - collecting cans
  - walking
- but controller consists of a collection of rules, possibly in layers
- BBS actually consist and are programmed in the behaviors, which are higher granularity, extended in time, capable of representation

expressing behaviors.

- behaviors can be expressed with various representations
- when a control system is being designed, the task is broken down into desired external behaviors
- those can be expressed with
  - functional notation
  - stimulus response (SR) diagrams
  - finite state machines/automata (FSA)
  - schema

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expressing behaviors: design paradigms.

- ethological guided/constrained
- situated activity
- experimentally driven

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expressing behaviors: functional notation.

- mathematical model:
  - represented as triples (S,R,β)
    - S = stimulus
    - R = range of response
    - β = behavioral mapping between S and R
- easily convert to functional languages like LISP

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expressing behaviors: functional example.

```
coordinate-behaviors [
   move-to-classroom (detect-classroom-location),
   avoid-objects (detect-objects),
   dodge-students ( detect-students ),
   stay-to-right-on-path ( detect-path ),
   defer-to-elders ( detect-elders )
] = motor-response
```

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expressing behaviors: FSA diagrams.

- states and transitions are most easily encoded in finite state automata and drawn as finite state diagrams
- states of the diagram can also be called behaviors
- diagrams show sequences of behavior transitions

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expressing behaviors: formal methods.

- used to verify intentions of designer (not the same as correctness of controller)
- enable automatic generation of code
- use a common language
- support formal analysis
- support high-level programming
- example: situated automata

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situated automata.

- formalism for specifying FSA's that are *situated* [Kaelbling & Rosenschein, 1991]
- task described in high-level logic expressions, as a set of goals and a set of operators that achieve (`ach`) and maintain (`maint`) the goals
- once defined, tasks can be compiled into circuits (using special purpose languages), which are reactive

expressing behaviors:

situated automata example.

```
(defgoalr (ach in-classroom)
   (if (not start0up)
      (maint (and (maint move-to-classroom)
                  (maint avoid-objects)
                  (maint dodge-students)
                  (maint stay-to-right-on-path)
                  (maint defer-to-elders)))))
```

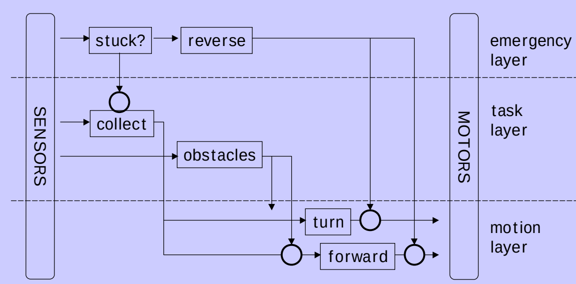

expressing behaviors:

subsumption architecture.

- Rodney Brooks, 1986
- MIT AI lab
- reactive elements
- behavior-based elements
- layered approach based on *levels of competence*

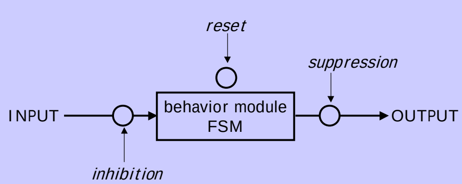
expressing behaviors:

subsumption architecture, 2.



expressing behaviors:

augmented finite state machine (AFSM).



behavioral encoding.

- behavioral response in physical space has a strength and an orientation
- expressed as (S,R,β)
- S = stimulus, necessary but not sufficient condition to evoke a response (R); internal state can also be used
- β = behavioral mapping categories
  - null
  - discrete
  - continuous

behavioral encoding: discrete encoding.

- expressed as a finite set of situation-response pairs/mappings
- mappings often include rule-based form IF-THEN
- examples:
  - Gapps [Kaelbling & Rosenschein]
  - subsumption language [Brooks]

behavioral encoding: continuous encoding.

- instead of discretizing the input and output, a continuous mathematical function describes the input-output mapping
- can be simple, time-varying, harmonic
- examples:
  - potential field
  - schema
- problems with local minima, maxima, oscillatory behavior

behavioral encoding: motor schemas.

- type of behavior encoding
- based on schema theory
- Ron Arbib, Georgia Tech
- provide large grain modularity
- distributed, concurrent schemas used
- based on neuroscience and cognitive science
- represented as vector fields
- decomposed into “assemblages” by fusion, not competition

behavioral encoding: assemblages.

- recursively defined aggregations of behaviors or other assemblages
- important abstractions for constructing behavior-based robots

behavioral encoding: schema representation.

- responses represented in uniform vector format
- combination through cooperative coordination via vector summation
- no predefined schema hierarchy
- arbitration not used -- gain values control behavioral strengths

behavioral encoding: designing with schemas.

- characterize motor behaviors needed
- decompose to most primitive level, use biological guidelines where appropriate
- develop formulas to express reactions
- conduct simple simulations
- determine perceptual needs to satisfy motor schema inputs
- design specific perpetual algorithms
- integrate/test/evaluate/iterate

behavioral encoding:
strengths and weaknesses.

- strengths
  - support for parallelism
  - run-time flexibility
  - timeliness for development
  - support for modularity
- weaknesses
  - niche targetability
  - hardware retargetability
  - combination pitfalls (local minima, oscillations)

representation.

- necessary in order to get benefits of BBS
- BBS representations are
  - distributed
  - matched to time-scale of the system
- constructed out of basic components of BBS system: behaviors

representation:
behavior.

- direct feedback loops/control laws: mapping sensors to effectors
- schemas: sensory or motor
- procedures: any combination
  - sensory
  - motor
  - sensory to motor
  - representational

representation:
example task: mapping.

- task: create a robot that can
  - move around safely
  - make a map of its environment
  - use the map to find paths to specific locations
- most common and useful mobile robot task
- many applications!

representation:
representing a map.

- representation needs to be
  - distributed
  - on a short time-scale
  - cannot be a traditional CAD-CAM centralized map

representation:
idea: distribute maps.

- distribute parts of map over different behaviors
- connect parts of the map that are adjacent in the physical world so that they are also adjacent in the map
- result is a network of behaviors representing the map
- map is topological

example: Toto.

- Maja Mataric, MIT now USC
- behavior-based robot
- first BBS robot to have a distributed representation
- control system consisted of a collection of behaviors
- lowest levels responsible for safe movement of robot (avoiding collisions)
- next levels responsible for keeping robot near walls, boundaries

Toto: landmarks.

- walls, corridors, messy irregular areas
- robot detected landmarks
- each landmark stored as a behavior
  - landmark type
  - compass heading
  - approximate length/size
- when a new landmark is found, a new behavior is added

Toto: landmarks, 2.

- adjacent landmarks connected by communication wires
- result is a topological representation of the environment
- also used for path finding

Toto: active map.

- whenever Toto visited a particular landmark, its associated map behavior would become activated
- if no behavior was activated, then the landmark was new, so a new behavior was created
- if an existing behavior was activated, it inhibited all other behaviors
- localization was based on which behavior was active

Toto: message passing.

- once Toto had a map, it could find paths from one landmark to another
- the goal behavior/landmark would send messages (send activation) to its neighbors, they would pass it on, etc
- eventually it would reach the current landmark (Toto's current position)

Toto: continuous map following.

- resulting string of behaviors is a path (or a plan) to the goal
- Toto did not store a string
- messages were passed continuously
- at each behavior in the map, Toto would decide where to go next
- goal reached one behavior at a time

Toto:

path optimization.

- at a junction, how did Toto decide where to go?
- path length computed based on landmark size and number of landmarks from goal to current landmark
- Toto chose shortest path

behavior coordination.

- BBS consist of collection of behaviors
- execution must be coordinated in a consistent fashion
- coordination can be
  - competitive
  - cooperative
  - combination of the two

behavior coordination:

deciding what to do next.

- action-selection problem
- behavior-arbitration problem

behavior coordination:

behavior arbitration.

- summing up
- average
- winner takes all

behavior coordination:

competitive coordination.

- perform arbitration (selecting one behavior among a set of candidates)
  - priority-based: subsumption
  - state-based: discrete event systems, Bayesian decision theory
  - function-based: spreading of activation action selection

behavior coordination:

cooperative coordination.

- perform command fusion (combine outputs of multiple behaviors)
- voting
- fuzzy (formalized voting)
- superposition (linear combinations)
  - potential fields
  - motor schemas
  - dynamical systems

emergent behavior.

- important but not well-understood phenomenon
- often found in behavior-based robotics
- robot behaviors “emerge” from
  - interactions of rules
  - interactions of behaviors
  - interactions of either with environment

emergent behavior: distinction.

- coded behavior
  - in the programming scheme
- observed behavior
  - in the eyes of the observer
  - emergence
- there is no one-to-one mapping between the two!

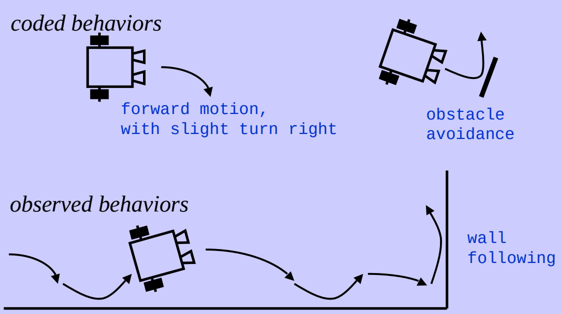
emergent behavior: is it magic?

- sum is greater than the parts
- emergent behavior is more than the controller that produces it

emergent behavior: interaction and emergence.

- interactions between rules, behaviors and environment
- source of expressive power for a designer
- i.e., systems can be designed to take advantage of emergent behavior

emergent behavior: example: wall following.



emergent behavior: example: wall following, 2.

- can be implemented with these rules:
  - if too far, move closer
  - if too close, move away
  - otherwise, keep on
- over time, in an environment with walls, this will result in wall-following
- is this emergent behavior?

emergent behavior:

emergent wall following.

- it is argued yes because
  - robot itself is not aware of a wall, it only reacts to distance readings
  - concepts of "wall" and "following" are not stored in the robot's controller
  - the system is just a collection of rules

emergent behavior:

emergent flocking.

- program multiple robots:
  - don't run into any other robot
  - don't get too far from other robots
  - keep moving if you can
- when run in parallel on many robots, the result is flocking

emergent behavior:

necessary conditions.

- notion of emergence depends on two aspects:
  - existence of an external observer, to observe and describe the behavior of the system
  - access to the internals of the controller itself, to verify that the behavior is not explicitly specified naywhere in the system

emergent behavior:

unexpected vs emergent.

- some researchers say the above is not enough for behavior to be emergent, because above is programmed into the system and the "emergence" is a matter of semantics
- so emergence must imply something unexpected, something "surreptitiously discovered" by observing the system

emergent behavior:

subjective expectations.

- "unexpected" is highly subjective, because it depends on what the observer was expecting
- naïve observers are often surprised!
- informed observers are rarely surprised

emergent behavior:

observation and emergence.

- once a behavior is observed, it is no longer unexpected
- is new behavior then "predictable"?

emergent behavior:
formalization.

- look for behaviors that are not apparent at system level (robot's controller) but are apparent at observer's level

emergent behavior:
execution and emergence.

- so now even simple wall following example given can be called "emergent"
- this means system has to execute in order for behavior to emerge

emergent behavior:
uncertainty and emergence.

- not difficult to achieve -- environment is uncertain, so exact behavior of a system is very hard to predict!
- if behavior contains novel and rich patterns, then it is "emergent"
- if world were completely predictable, then we'd remove "emergent behaviors" by this definition

emergent behavior:
emergence is unavoidable.

- some interesting and unexpected behaviors will always emerge in systems that interact with the physical world
- some may be labeled "emergent"
- some are not desirable!

emergent behavior:
emergent bugs.

- unexpected, emergent behavior that is undesirable
- e.g., oscillations
- try to avoid them, but still want to exploit desirable, unexpected behaviors
- system needs to know how to distinguish between the two

emergent behavior:
sequential vs parallel.

- emergent behaviors can arise from parallel execution of multiple behaviors (e.g., flocking)
- also from sequential interaction with an interesting environment

emergent behavior:

architectures and emergence.

- different architectures affect the likelihood of generating and using emergent behaviors
- deliberative: always aim to eliminate them
- reactive: aim to exploit them
- hybrid: typically aim to eliminate them
- BBS: aim to exploit them

emergent behavior:

modularity and emergence.

- modularity directly effects emergence
- reactive and BBS employ parallel rules and behaviors which interact with each other and the environment, thus directly producing and exploiting emergent behavior

emergent behavior:

avoiding & exploiting.

- hybrid systems follow deliberative model in attempt to produce a coherent, uniform output of the system, minimizing interactions and emergence

reading.

- *Behavior-Based Robotics*, chapter 3, by Ron Arkin, course pack 2 p203-261
- *Behavior-based Robotics, its scope and its prospects*, by Andreas Birk, course pack 2 p263-268