History of Intelligent Robotics

August 29, 2002

Class Meeting 3
Announcement

• Remember Assignment #1 is due at beginning of class next time
Objectives

• Understand historical precursors to intelligent robotics:
  – Cybernetics
  – Artificial Intelligence
  – Robotics

• Become familiar with key milestones in development of intelligent robotics

• Understand overall approaches to robotic control taken by historical precursors
Historical Precursors to Today’s Intelligent Robotics

- Cybernetics
  - Grey Walter’s tortoise
- Artificial Intelligence
  - Dartmouth Conference
  - AI Planning Tradition
  - Shakey (SRI)
  - HILARE (LAAS)
- Robotics
  - Stanford Cart
  - Planetary rovers
  - Telerobotics
  - Manufacturing

Timeline:
- 1950
- 1960
- 1970
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- 2000
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Cybernetics

- Cybernetics is combination of:
  - Control theory
  - Information science
  - Biology

- Seeks to explain control principles in both animals and machines

- Uses mathematics of feedback control systems to express natural behavior

- Emphasis is on situatedness -- strong two-way coupling between organism and its environment

- Leader of cybernetics field: Norbert Wiener in late 1940s
Grey Walter’s *Machina Speculatrix*, or Tortoise (1953)

- **Sensors:**
  - Photocell
  - Contact
- **Actuators:**
  - Steering motor on wheel
  - Driving motor on wheel
- **Behaviors of tortoise:**
  - Seeking light
  - Head toward weak light
  - Back away from bright light
  - Turn and push (for obstacle avoidance)
  - Recharge battery
Principles Learned from Walter’s Tortoise

• Parsimony: simple is better

• Exploration or speculation: constant motion to avoid traps

• Attraction (positive tropism): move towards positive stimuli

• Aversion (negative tropism): move away from negative stimuli

• Discernment: distinguish between productive and unproductive behavior
Braitenberg’s Vehicles (1984)

- Took perspective of psychologist
- Created wide range of vehicles
- Vehicles used inhibitory and excitatory influences
- Direct coupling of sensors to motors
- Exhibited behavioral characteristics that appeared to be:
  - Cowardice
  - Aggression
  - Love
  - (Etc.)
Braitenberg Vehicle 1: “Getting Around”

- Single motor, single sensor
- Motion always forward
- Speed controlled by sensor
- Environmental perturbations produce direction changes
Braitenburg Vehicle 2: “Fear and Aggression”

- Two motors, two sensors
- One configuration: light aversive (“fear”)
- Second configuration: light attractive ("aggression")
Braitenburg Vehicle 3: “Love and Exploration”

- Two motors, two sensors
- Same as vehicle 2, but with inhibitory connections
- One configuration: approaches and stops at strong light (“love”)
- Second configuration: approaches light, but always exploring (“explorer”)
Braitenburg Vehicle 4: “Values and Special Tastes”

• Two motors, two sensors
• Add various non-linear speed dependencies to vehicle 3, s.t. speed peaks between max and min intensities
• Result: oscillatory behaviors
Summary of Braitenberg’s Vehicles

• Systems are inflexible, non-reprogrammable

• However, vehicles are compelling in overt behavior

• Achieve seemingly complex behavior from simple sensorimotor transformations
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Artificial Intelligence (AI)

• Beginnings of AI: Dartmouth Summer Research Conference (1955)
• Original topics studied:
  – Language
  – Neural nets
  – Complexity theory
  – Self-improvement
  – Abstractions
  – Creativity
• Marvin Minsky: an intelligent machine “would tend to build up within itself an abstract model of the environment in which it is placed. If it were given a problem it could first explore solutions within the internal abstract model of the environment and then attempt external experiments.”
Early AI Roots Strongly Influenced Research

• Through mid-80’s, AI research strongly dependent upon:
  – Representational knowledge
  – Deliberative reasoning methods
  – Hierarchical organization
Classical AI Methodology

- **Key characteristics:**
  - The ability to represent hierarchical structure by abstraction
  - The use of “strong” knowledge using explicit symbolic representation
- **Beliefs:**
  - Knowledge and knowledge representation are central to intelligence
  - Robotics is no exception
- **Focus:**
  - Human-level intelligence
- **Not of interest:**
  - Animal-level intelligence
Early Robotics Development

Shakey (SRI), 1960’s

• One of first mobile robots

• Sensors:
  – Vidicon TV camera
  – Optical range finder
  – Whisker bump sensors

• Environment: Office environment with specially colored and shaped objects

• STRIPS planner: developed for this system
  – Used world model to determine what actions robot should take to achieve goals
HILARE (LAAS-CNRS), 1970’s

- **Sensors**: Video camera, 14 sonar, laser range finder
- **Three wheels**: two drive, one caster
- **Weight**: 400 kg
- **World**: smooth floors, office environment
- **Planning**: Conducted in multi-level geometric representational space
- **Use**: for experimentation for over a decade
Stanford Cart, 1970’s (Moravec)

- **Sensors:** Stereo vision used for navigation

- **Speed:** Very slow, moving at about 1 meter per 10-15 minutes

- **Full run:** 5 hours

- **Obstacles:** added to internal map as enclosing spheres

- **Search:** Used graph search algorithm to find shortest path

- **Accomplishments:** Successfully navigated complex 20-meter courses, visually avoiding obstacles
Early Robotics Development (con’t.)

**CMU Rover, 1980’s**

- Follow-on to Stanford Cart
- **Sensors:**
  - Camera mounted on pan/tilt
  - Infrared and sonar sensors
- **Actuators:** Three independently powered/steered wheels
- **Accomplishments:** Set stage for upcoming behavior-based robotics
Planning-Based Approach to Robot Control

• Job of planner: generate a goal to achieve, and then construct a plan to achieve it from the current state.

• Must define representations:
  – Representation of actions: programs that generate successor state descriptions
  – Representation of states: data structure describing current situation
  – Representation of goals: what is to be achieved
  – Representation of plans: solution is a sequence of actions

 Typically: Use first-order logic and theorem proving to plan strategies from start state to goal
First Order Predicate Calculus in AI

• First order predicate calculus: formal language useful for making inferences and deductions

• Elementary components:
  – Predicate symbols (e.g., WRITES(), LIVES(), OWNS(), MARRIED())
  – Variable symbols (e.g., x, y)
  – Function symbols (e.g., father(x) returns the father of x)
  – Constant symbols (e.g., HOUSE-1, NERO, GEORGE-BUSH)
  – Connectives
    • and, or, negation, implies \( \land, \lor, \neg, \implies \)
  – Quantification
    • Universal \( \forall x \)
    • Existential \( \exists x \)

• NOTE: First order means quantification over predicates or functions not allowed
Use Rules of Inference, Unification to Prove Theorems

• **Rules of inference:**
  - \( P \) and \( \sim P \lor Q \) resolves to \( Q \) (modus ponens)
  - \( P \lor Q \) and \( \sim P \lor Q \) resolves to \( Q \)
  - \( P \lor Q \) and \( \sim P \lor \sim Q \) resolves to \( Q \lor \sim Q \) and \( P \lor \sim P \)
  - \( \sim P \) and \( P \) resolves to \( \text{Nil} \)
  - Etc.

• **Unification:**
  - Finding substitutions of terms for variables to make expressions identical
  - Equivalent to symbolic pattern matching
  - E.g.: Add-List: \( \text{ON}(x,y) \) can be made equivalent to \( \text{ON}(A,B) \) through substitution and unification
Many AI Planners Developed From these Concepts

• Well-known AI Planners:
  – STRIPS (Fikes and Nilsson, 1971): theorem-proving system
  – ABSTRIPS (Sacerdoti, 1974): added hierarchy of abstractions
  – HACKER (Sussman, 1975): use library of procedures to plan
  – NOAH (Sacerdoti, 1975): problem decomposition and plan reordering
STRIPS-Based Approach to Robot Control

- Use first-order logic and theorem proving to plan strategies from start state to goal

- Define:
  - Goal State
  - Initial State
  - Operators

- STRIPS Operators have:
  - Action description
  - Preconditions
  - Effect:
    - Add-list
    - Delete-list
Simple Example of STRIPS-Style Planning

• Goal State: ON(A,B)
• Start state: ON(A, Table); ON(B, Table); EMPTYTOP(A); EMPTYTOP(B)
• Operator:
  – MOVE(x,y):
    • Preconditions: ON(x,Table); EMPTYTOP(y)
    • Add-List: ON(x,y)
    • Delete-List: EMPTYTOP(y); ON(x,Table)
Shakey’s STRIPS World

• Types of actions Shakey can make (at least in simulation):
  – Move from place to place:
    Go(y):
      PRECOND: At(Shakey,x)
      In(x,r) \land In (y,r)
      On(Shakey,Floor)
      EFFECT: At(y)
  – Push movable objects:
    Push(b, x, y):
      PRECOND: Pushable(b)
      At(b,x)
      At(Shakey,x)
      In(x,r) \land In (y,r)
      On(Shakey,Floor)
      EFFECT: At(b,y)
Shakey’s STRIPS World (con’t.)

• Types of actions Shakey can make (at least in simulation):
  – Climb onto rigid objects:
    Climb(b):
    PRECOND: Climbable(b)
    At(Shakey,x) \land At(b,x)
    On(Shakey,Floor)
    EFFECT: On(Shakey,b)

  – Climb down from rigid objects:
    (etc.)

  – Turn light switches on and off:
    (etc.)
Challenges of AI and Planning Systems

• Closed world assumption: Assumes that world model contains everything the robot needs to know: there can be no surprises

• Frame problem: How to represent real-world situations in a manner that is computationally tractable

• Open world assumption: means that the closed world assumption cannot apply to the given domain
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Behavior-Based Robotics’ Response to Classical AI

• Reacted against classical AI

• Brooks (1987-1990):
  “Planning is just a way of avoiding figuring out what to do next”
  “Elephants don’t play chess”

• Increased emphasis on:
  – Sensing and acting within environment

• Reduced emphasis on:
  – Knowledge representation
  – Planning
Wide Spectrum of Robot Control

- Deliberative
  - Purely symbolic
  - Speed of response: Slower response
  - Predictive capabilities: High-level intelligence (cognitive)
  - Dependence on accurate, complete world models: Representation-dependent
  - Representation: Slower response, High-level intelligence (cognitive), Variable latency

- Reactive
  - Reflexive
  - Speed of response: Real-time response
  - Predictive capabilities: Low-level intelligence
  - Dependence on accurate, complete world models: Representation-free
  - Representation: Real-time response, Low-level intelligence, Simple computation
Deliberative Control

• **Common characteristics:**
  – Hierarchical in structure
  – Clearly identifiable division of functionality
  – Communication and control is predictable and predetermined
  – Higher levels provide subgoals for lower levels
  – Planning scope changes with descent in hierarchy
  – Heavy reliance on symbolic representations

• Seemingly well-suited for structured and highly predictable environments (e.g., manufacturing)
Example Deliberative Architecture: NASREM

- Developed by Albus, mid-80’s
- Multiple layers
- Each layer has:
  - Sensory processing
  - World modeling
  - Task decomposition
  - Value judgement
- All layers joined by global memory through which representational knowledge is shared
- Perception is not tied directly to action
NASREM Endorsed as Standard Model in 1980’s

- Six levels capture specific functionalities:
  - Servo
  - Primitive
  - Elemental move
  - Task
  - Service bay
  - Service mission

- Despite government endorsement, only limited acceptance
Other Deliberative Architectures

- RCS (Real-time Control System): similar to NASREM
- Drexel University’s Nested hierarchical intelligent controller
- RPI model: restricted to 3 layers -- organization, coordination, and execution
Drawbacks to Deliberative Control led to Reactive Control

• **Shortcomings:**

  – Lack of responsiveness in unstructured and uncertain environments, due to:
    • Requirements of world modeling
    • Limited communication pathways

  – Difficulty of engineering complete systems incrementally
Reactive Control

- **Definition**: a technique for tightly coupling perception and action, typically in the context of motor behaviors, to produce timely robotic response in dynamic and unstructured worlds.

- **Individual behavior**: a stimulus/response pair for a given environmental setting that is modulated by attention and determined by intention

- **Attention**: prioritizes tasks and focuses sensory resources; determined by current environmental context

- **Intention**: determines set of behaviors that should be active based on internal goals and objectives

- **Overt or emergent behavior**: the global behavior of robot as consequence of interaction of active individual behaviors

- **Reflexive behavior**: behavior generated by hardwired reactive behaviors with tight sensor-effector loop, using no world models
Key Issues of Behavior-Based Control

- **Situatedness**: robot operates in the real world

- **Embodiment**: robot has a physical presence (body)

- **Emergence**: Intelligence arises from interaction of robot with environment

- **Grounding in reality**: avoid symbol grounding problem

- **Ecological dynamics**: cannot characterize environment

- **Scalability**: Unknown whether behavior-based control will scale to human-level intelligence
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Telemanipulators and Telerobotics

• Teleoperation: human operator controls robot remotely through mechanical or electronic linkages

• Operator and robot:
  – Leader/follower relationship
  – Human leads, robot mimics human behaviors

• Issues include:
  – Force feedback
  – Operator telepresence
  – Supervisory control

• Challenges:
  – Operator overload
  – Cognitive fatigue
  – Simulator sickness

ORNL Telemanipulator Projects
Space Robotics

• Planetary rovers:
  – One-of-a-kind
  – Significant consequences of failure

• Sojourner robot:
  – Part of PathFinder Mars Mission
  – Very successful robot
  – Explored MARS from July 5 – Sept. 27, 1997
  – Fully teleoperated
Eventually, Space Robotics May Move More Toward Intelligent Robotics

Challenge: Proving capabilities of autonomous systems

Nanorover, prototype for comet mission

Rocky 7, with stereo vision and sampling manipulator

Gofer, with active center of gravity compensation
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- AI Robotics

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Summary

• Many threads of robotics-related research:
  – Cybernetics
  – Artificial intelligence
  – Intelligent robot precursors

• Primary ongoing directions:
  – Intelligent (AI) robotics
  – Telerobotics
  – Space robotics
Preview of Next Class

- So far this semester: Breadth-first coverage of material
- Rest of semester: Depth-first study of many individual topics

- Next time: Hierarchical Paradigm and STRIPS, in-depth