History of Intelligent Mobile Robotics
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)

• Robotics
  - Stanford Cart
  - HILARE (LAAS)
  - Planetary rovers
  - Telemanipulators
  - Telerobotics
  - Telerobotics
  - Manufacturing

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
W. Grey Walter

• Born in Kansas City in 1910, but raised in Cambridge, England
• Did work in 1920s with EEG
• Showed that certain patterns indicated person is learning
• Led to work in artificial intelligence and robotics

W. Grey Walter and one of his robots
Grey Walter’s *Machina Speculatrix*, or Tortoise (1953)

- **Behaviors of tortoise:**
  - Seeking light
  - Head toward weak light
  - Back away from bright light
  - Turn and push (for obstacle avoidance)
  - Recharge battery

- **Sensors:**
  - Photocell
  - Contact

- **Actuators:**
  - Steering motor on wheel
  - Driving motor on wheel
**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.)

Valentino Braitenberg
Former Director
Max Plank Institute for Biological Cybernetics, Germany
What behaviors do you see?

• (Movie of some of Braitenberg’s vehicles)
Braitenburg 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”)

![Diagram of Braitenburg Vehicle 3 with light source and arrows indicating movement patterns.](image-url)
Braitenberg 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
What would you expect of this vehicle?
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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  - Telerobotics (Manufacturing)

Timeline:
- 1950
- 1960
- 1970
- 1980
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- 2000
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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
Early Robotics Development (con’t.)

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: 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 \( \wedge, \vee, \neg, \implies \)
  – 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 \( \neg P \lor Q \) resolves to \( Q \) (modus ponens)
  – \( P \lor Q \) and \( \neg P \lor Q \) resolves to \( Q \)
  – \( P \lor Q \) and \( \neg P \lor \neg Q \) resolves to \( Q \lor \neg Q \) and \( P \lor \neg P \)
  – \( \neg P \) and \( P \) resolves to \textit{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)
• Types of actions Shakey can make (at least in simulation):
  – Move from place to place:
    Go(y):
      PRECOND: At(Shakey,x)
      ln(x,r) ∨ ln (y,r)
      On(Shakey,Floor)
      EFFECT: At(y)
  – Push movable objects:
    Push(b, x, y):
      PRECOND: Pushable(b)
      At(b,x)
      At(Shakey,x)
      ln(x,r) ∨ ln (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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Dartmouth Conference
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

Now typically called “New AI”
Wide Spectrum of Robot Control

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

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

- **NASREM**: NASA Standard Reference Model for Telerobots
- 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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AI Robotics
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
Current Robots on Mars: *Opportunity* and *Spirit*

Landed on Mars in January 2004 – still operational!
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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Summary

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

• Primary ongoing directions:
  – Intelligent (AI) robotics
  – Telerobotics
  – Space robotics