Introduction

Version: 15.10.03

What is a robot?

- Notion derives from 2 strands of thought:
  - Humanoids – human-like
  - Automata – self-moving things
- "Robot" – derives from Czech word robota
  - "Robota": forced work or compulsory service
- Term coined by Czech play right Karel Capek
  - 1921 play "R.U.R." (Rossum's Universal Robots)
- Current notion of robot:
  - Programmable
  - Mechanically papable
  - Flexible
- Our Working definition of robot: physical agent that generates "intelligent" connection between perception and action

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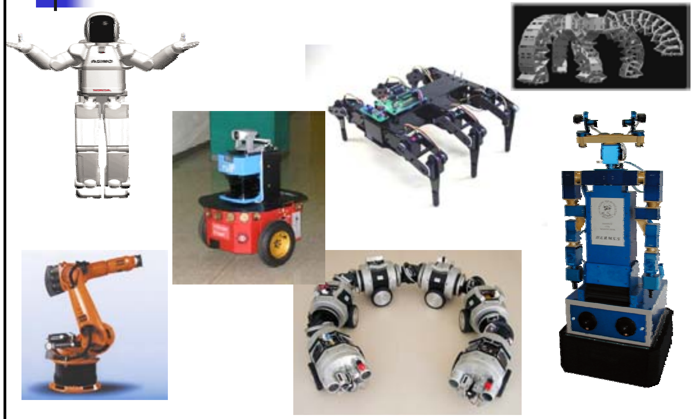
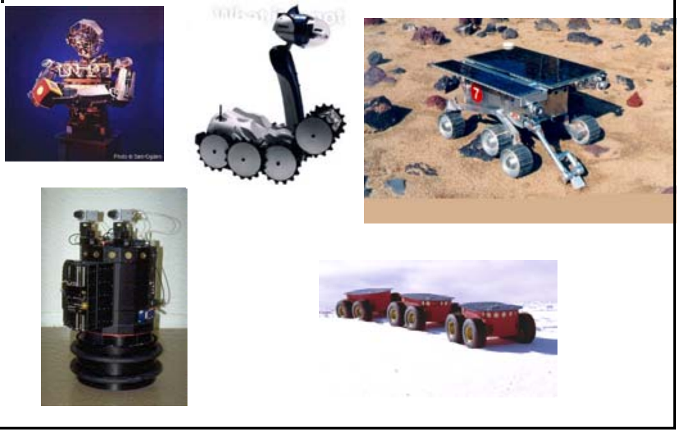
Some Current State-of-the-Art Robots

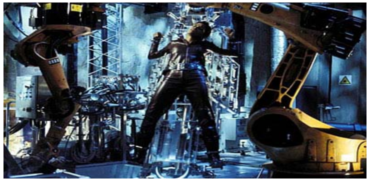


More State-of-the-Art Research Robots



Robot Videos

- Industrial manipulators



- Honda Humanoid Robot
  - http://world.honda.com/ASIMO
  - walking
  - stair climbing

Robot Videos

- Localization and Navigation
- ..\Videos\103_0363.AVI

Robotics as an Interdisciplinary Science

- Mathematics
- Physics
- Control-theory
- Cybernetics
- Computer Science
- Artificial Intelligence
- Biology
- Psychology
- Sociology
- Philosophy
- Artificial life

Why Are Mobile Robots Interesting ?

- Mobile robots are a motivating and hard test environment for a wide range of methods.
- The success of each method can be evaluated according to the following criteria, which can be categorized in three fields:
  - Real-world abilities, meaning the ability of handling real-world data
  - Interacting with the environment
  - Handling dynamic scenes

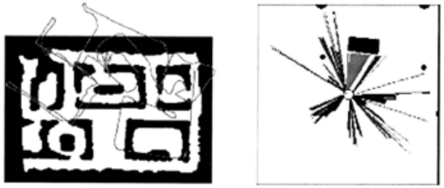
State of Robotics Applications

- Moving from manufacturing, industrial manipulators to:
  - Entertainment robotics
  - Personal service robots
  - Medical robots
  - Industrial applications beyond factory (e. g., mining, agriculture)
  - Hazardous applications (e. g., military, toxic cleanup, space)

Challenges of Robotics Research: Inherent Uncertainty (1)

- Environment is stochastic and unpredictable
- Sensors are limited and noisy
- Robot effectors are limited and noisy
- Models are simplified and inaccurate

Example:



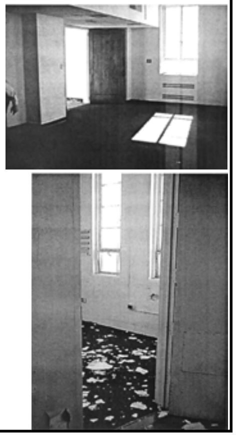
Challenges of Robotics Research: Inherent Uncertainty (2)

Examples:

laser scan with raw odometry data

map based on corrected odometry data

Sources and Effect of Uncertainty/Noise

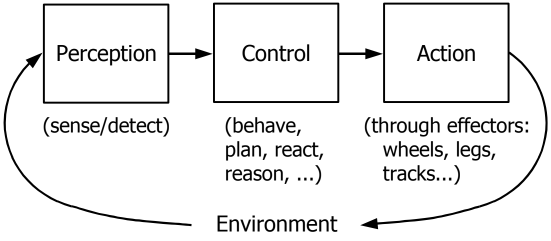


- Sources of sensor noise:
  - Limited resolution sensors
  - Sensor reflection, multi-pathing, absorption
  - Poor quality sensor conditions (e.g., low lighting for cameras)
- Sources of effectors noise:
  - Friction: constant or varying (e.g., carpet vs. vinyl vs. tile; clean vs. dirty floor)
  - Slippage (e.g., when turning or on dusty surface)
  - Varying battery level (drainage during mission)
- Impact:
  - Sensors difficult to interpret
  - Same action has different effects when repeated
  - Incomplete information for decision making

Why is Robotics hard?

- Sensors are limited and crude
- Effectors are limited and crude
- State (internal and external, but mostly external) is partially-observable
- Environment is dynamic (changing over time)
- Environment is full of potentially-useful information

What are Basic Robot Issues?



- How do you perceive?
- How do you control?
- How do you generate action?

Intelligent Robotics

- Autonomous mobile robots accomplish given objectives in unstructured, dynamic, partially observable, and uncertain environments:
  - Autonomous: robot makes majority of decisions on its own; no human-in-the-loop control (as opposed to teleoperated)
  - Mobile: robot does not have fixed based (e. g., wheeled, as opposed to manipulator arm)
  - Unstructured: environment has not been specially designed to make robot’s job easier
  - Dynamic: environment may change unexpectedly
  - Partially observable: robot cannot sense entire state of the world (i. e., “hidden” states)
  - Uncertain: sensor readings are noisy; effecter output is noisy

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Fundamental Issues in Robotics

-Where am I? [localization]

- How do I interpret my sensor feedback to determine my current state and surroundings? [sensor processing / perception]
- How do I make sense of noisy sensor readings? [uncertainty management]
- How do I fuse information from multiple sensors to improve my estimate of the current situation? [sensor fusion]
- What assumptions should I make about my surroundings? [structured / unstructured environments]
- How do I know what to pay attention to [focus-of-attention]

Fundamental Issues in Robotics

-What should my control strategy be to ensure that I respond quickly enough? [control architecture]

- How should I make decisions? [reasoning, task arbitration]

- Where do I want to be, and how do I get there? [path planning, navigation]

- I have lots of choices of actions to take – what should I do in my current situation? [action selection]

- How should I change over time to respond to a dynamic environment? [learning, adaptation]

- Why doesn't the same action that worked in this situation before not work now? [hidden state]

- How should I work with other robots? [multi-robot cooperation, communication]

Components of a Robot

- sensors
- effectors/actuators
- locomotion system
- on-board computer system

Sensors

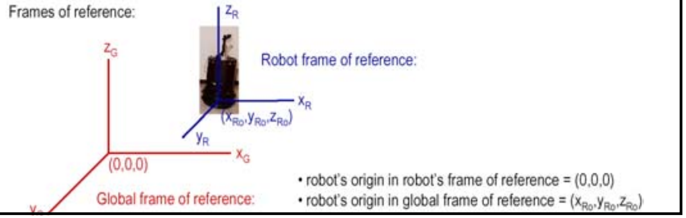
- Sonars
- Laser range scanners
- Infrared proximity detectors
- Cameras
- Bumpers, tactile sensors
- Encoders
- Accelerometers, compass, gyroscope, inertial navigation systems
- GPS

Sensor Modalities

- Sensor modality:
  - Sensors which measure same form of energy and process it in similar ways
  - "Modality" refers to the raw input used by the sensors
- Different modalities:
  - Sound
  - Pressure
  - Temperature
  - Light
    - Visible light
    - Infrared light
    - X-rays
    - etc.

Categorizing Perceptual Stimuli

- Proprioception: measurements of movement relative to the robot's internal frame of reference (also called *dead reckoning*)
- Exteroception: measurements of layout of the environment and objects relative to robot's frame of reference
- Exproprioception: measurement of the position of the robot body or parts relative to the layout of the environment



- robot's origin in robot's frame of reference = (0,0,0)
- robot's origin in global frame of reference = (x_{Ro}, y_{Ro}, z_{Ro})

Proprioceptive Sensors

- Sensors that give information on the internal state of the robot, such as:
  - Motion
  - Position (x, y, z)
  - Velocity, acceleration
  - Temperature
  - Battery level
- Example proprioceptive sensors:
  - Encoders (dead Reckoning)
  - Inertial navigation system (INS)
  - Global positioning system (GPS)
  - Compass
  - Gyroscopes

Dead Reckoning Odometry Encoders

- Measure turning distance of motors (in terms of numbers of rotations), which can be converted to robot translation/rotation distance
- If gearing and wheel size known, number of motor turns → number of wheel turns → estimation of distance robot has traveled

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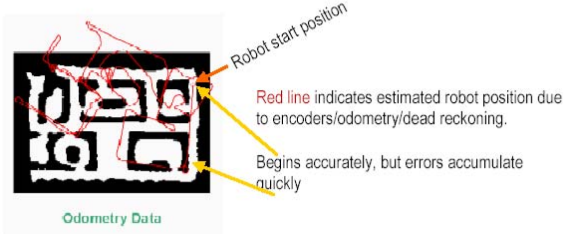
Encoders

- Challenges/issues:
  - Motion of wheels not corresponding to robot motion, e.g., due to wheel spinning
  - Wheels don't move but robot does, e.g., due to robot sliding
- Error accumulates quickly, especially due do turning:



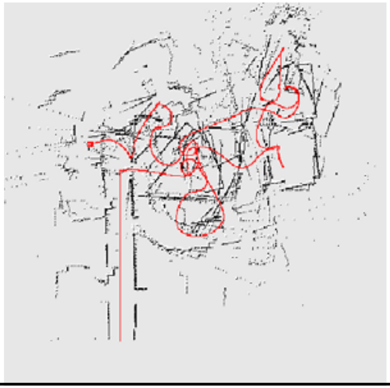
Red line indicates estimated robot position due to encoders/odometry/dead reckoning.

Begins accurately, but errors accumulate quickly

Odometry Data

Dead Reckoning Errors

- Plot of overlaid laser scans overlaid based strictly on odometry:



Proximity Sensors

- Measure relative distance (range) between sensor and objects in environment
- Most proximity sensors are active
- Sonar (ultrasonics)
- Laser range finders
- Infrared (IR)
- Bump and feeler sensors

Time of Flight Sensors

$$d = v\ t$$

d : round-trip distance
v : speed of propagation
t : elapsed time.

The measured time is representative of traveling twice the separation distance (i. e., out and back) and must therefore be reduced by half to result in actual range to the target.

Errors for Time of Flights Sensors

- Variations in the speed of propagation, particularly in the case of acoustical systems
- Uncertainties in determining the exact time of arrival of the reflected pulse
- Inaccuracies in the timing circuitry used to measure the round-trip time of flight
- Interaction of the incident wave with the target surface

Sonar (Ultrasonics)

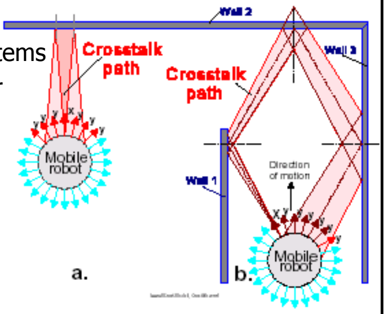
- Refers to any system that achieves ranging through sound
- Can operate at different frequencies
- Very common on indoor and research robots
- Operation:
  - Emit a sound
  - Measure time it takes for sound to return
  - Compute range based on *time of flight*

Reasons Sonar is So Common

- Can typically give 360° coverage as polar plot
- Cheap (a few $US)
- Fast (sub-second measurement time)
- Good range – about 25 feet with 1” resolution over FOV of 30°

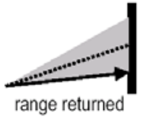
Ultrasonic Sensors

- Ultrasonic TOF ranging is today the most common technique employed on indoor mobile robotics systems.
- availability of low-cost systems
- Sonar sensors are used for
  - world modeling
  - collision avoidance,
  - position estimation
  - motion detection.

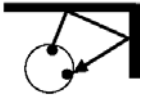


Sonar Challenges

- “Dead zone”, causing inability to sense objects within about 11 inches
- Indoor range (up to 15 feet) better than outdoor range (perhaps 8 feet)
- Key issues:
  - Foreshortening:



  - Cross-talk: sonar cannot tell if the signal it is receiving was generated by itself, or by another sonar in the ring



Mobile Robots and Manipulators

- A robot acts through the use of its actuators, also called effectors.
- Robotic actuators are used for:
  - locomotion (moving around, going places)
  - manipulation (handling objects)
- Mobile robotics
  - Mobile robots can move around, using wheels, tracks, or legs, and usually move in 2-dimensions;
- Manipulator robotics
  - Manipulators are various robot arms
  - 6-DOF arms can move in three translational and three rotational dimensions

Brief History of Robotics

- Cybernetics
- Grey Walter's Tortoise
- Breitenberg Vehicles
- Shakey
- Behavior Based Paradigm

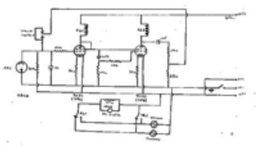
Cybernetics

- 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

Cybernetics

- Pioneered by Norbert Wiener (1940s) (From Greek "steersman" of steam engine)
- Marriage of control theory (feedback control), information science and biology
- Seeks principles common to animals and machines, especially for control and communication
- Coupling an organism and its environment (situatedness)

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

Design Principles Learned from Walter's Tortoise

- Parsimony: simple is better (recharging strategy)
- Exploration or speculation: constant motion to avoid traps
- Attraction (positive tropism): move towards positive stimuli
- Aversion (negative tropism): motivation to avoid obstacles, slopes
- Discernment: distinguish between productive and unproductive behavior

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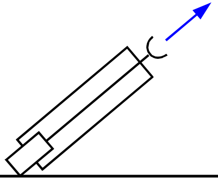
Braitenberg's Vehicles (1984)

- Took perspective of psychologist
- Created wide range of vehicles
- Vehicles used inhibitory and excitatory influences
- Direct coupling of sensors to motors
- Complex behaviors from simple mechanisms
- Exhibited behavioral characteristics that appeared to be:
  - Cowardice
  - Aggression
  - Love
  - etc.

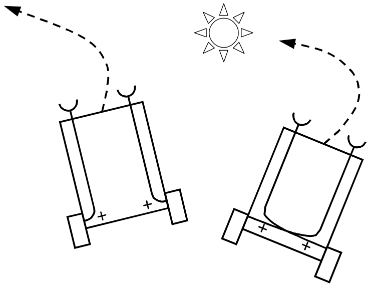
Braitenberg Vehicle 1: „Getting Around"

- Single motor, single sensor
- Motion always forward
- Speed controlled by sensor
- Principle: The more there is of the quality (e.g., heat) to which the sensor is tuned, the faster the motor goes.
- Environmental perturbations produce direction changes



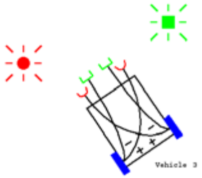
Braitenberg Vehicle 2:

- Two motors, two sensors
- One configuration: light aversive (“fear”)
- Second configuration: light attractive (“aggression”)



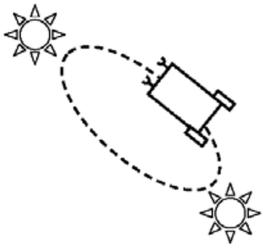
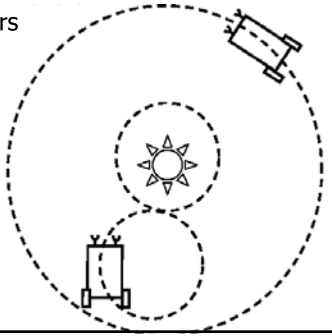
Braitenberg Vehicle 3: „ Love and Exploration“

- 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 sensori-motor transformations

Shakey (SRI), 1960‘s

- One of first mobile robots
- Sensors:
  - Vidicon TV camera
  - Optical range finder
  - Whisker bump sensors
- Radio link to DEC PDP-10 , PDP-15 computers
- 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

Shakey

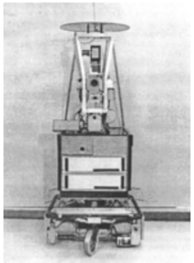
Shakey used

- programs for perception, world-modeling, and acting.
- low level action routines took care of simple moving, turning, and route planning.
- intermediate level actions strung the low level ones together in ways that robustly accomplished more complex tasks.
- the highest level programs could generate and execute plans to achieve goals given it by a user.
- the system also generalized and saved these plans for possible future use.

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) $\wedge$ In(y, r)
EFFECT: At (y)



- Push movable objects:

Push (b, x, y):
PRECOND: Pushable (b)
At (b, x)
At (Shakey,x)
In (x, r) $\wedge$ In(y, r)
On (Shakey, Floor)
EFFECT: At (b, y)

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)
    - Add-List: ON(x,y)
    - Delete-List: EMPTYTOP (y); ON (x, Table)