ROBOTICS

Classical Definition of Robot

- A robot is a re-programmable, multi-functional, manipulator designed to move material, parts, or specialized devices though variable programmed motions for the performance of a task (Robotics Industry Association)

What is a robot?

- An intelligent robot is a machine able to extract information from its environment and use knowledge about its world to move safely in a meaningful and purposeful manner (Mataric).
- A robot is a system which exists in the physical world and autonomously senses its environment and acts in it.

Where did the word 'robot' come from?

- The word 'robot' was coined by the Czech playwright Karel Capek from the Czech word for forced labor or serf.
- The use of the word Robot was introduced into his play R.U.R. (Rossum's Universal Robots) which opened in Prague in January 1921.

Robotics as an Interdisciplinary Science

- Arts,
- Politics,
- Economics,
- Mathematics,
- Physics,
- Control-theory,
- Cybernetics,
- Computer Science,
- Artificial Intelligence,
- Biology,
- Psychology,
- Sociology,
- Social-Psychology,
- Philosophy,
- Artificial life,
- Sports

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, of interacting with the environment, and of handling dynamic scenes.

Why Are Mobile Robots Interesting ?

- Adaptability or learning abilities of a mobile robot including subcriteria like spontaneous learning, stable learning, etc.
- Cognitive complexity or competence, expressed by the ability of symbolic or qualitative reasoning.

Brief History of Robotics

Automata

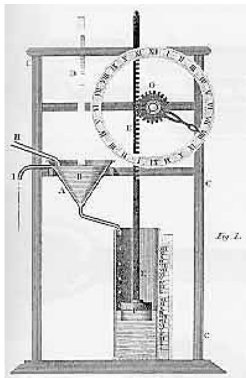
- The first complex machines produced by man were automata, by means of which he attempted to simulate nature and domesticate natural forces.
- They constituted the first step in the realization of his dream to fly through the air like a bird, swim the sea like a fish, and to become ruler of all nature.
- From these attempts to imitate life by mechanical means, man subsequently utilized the principles involved to produce the complex mechanisms which have resulted in the technological advances of the Space Age.

Egypt

- At the height of Egyptian civilization 3,000 years ago, articulated statues could be controlled by hidden operators.
- One is a painted head of the Jackal God of the Dead, and
- the other a large white limestone bust of the God Re-Harmakhis.
- Each had a hollow tube leading down from the mouth so that a hidden priest could make the statue talk.

Ctesibus

- Around 270 BC, Ctesibus produced the first organ and clepsydra (water clock) with moving figures.

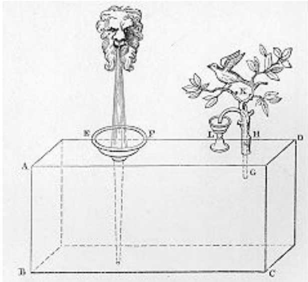


Marcus Vitruvius Pollio

- The Greek tradition was revived by Vitruvius, who in (c. 90-20 B.C.E.) *De Architectura* described several automata and developed the canon of proportions, which is the basis of classical anatomical aesthetics.

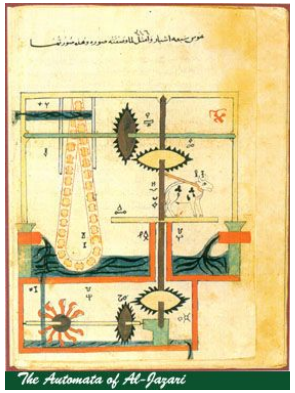
Hero of Alexandria

- Hero of Alexandria (ca 62 A.D.) detailed several automata that were used in theater and for religious purposes.
- He wrote extensively of water actuated automatic devices in his pneumatics.
- Included were
  - singing bird figures,
  - magic goblets and vases in variety,
  - self opening and closing doors,
  - self lighting and extinguishing fires and
  - many other fascinating items.



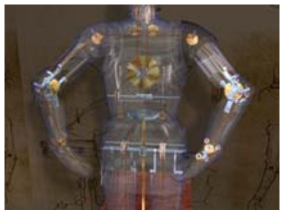
Al-Jazari

- Islam authors also designed complex mechanical arrangements. Al-Jazari, for instance, illustrated several designs which also anticipated the principle of the modern flush toilet



Leonardo's robot

- Leonardo da Vinci, designed a mechanical equivalent of a human—a humanoid robot—around 1475; unfortunately, the design has still not been constructed.
- The robot is fitted with a visor that rises automatically, revealing the articulation of the jaw.
- The device can also alternately open and close its arms.
- A mechanical, analog-programmable controller inside the chest provides power and control for the arms via a cylindrical, grooved cam that triggers high-torque worm gears attached to a central pulley.
- The robot also moves its wrists and thumbs.



Androids

- The first real android in human form that has been recorded is thought to have been built by Hans Bullmann or Nuremberg, possibly about 1525.
- He is known to have made quite a few moving figures of both men and women, some of which played musical instruments.

Gianello Torriano

- One of Gianello Torriano of Cremona (ca 1515 - 1585) figures, that of a woman lute player, survived and is now in the Kunsthistorisches Museum in Vienna.
- The mechanical doll plays the lute, turns its head and seems to mince along with tiny steps while in fact running on wheels.

Jacques de Vaucanson

- Jacques de Vaucanson (1709-1782) built three clockwork humanoids.
- One was a mandolin player that sang and tapped foot as it played.
- Another was a piano player that simulated breathing and moved its head.
- A third was a flute player.
- All were reported to be very lifelike, though none could sense the environment; all were simple playback mechanisms.

- In the 18th century Pierre Jacquet-Droz, a Swiss watchmaker, and his son Henri-Louis built a number of humanoids, including a female organ player that simulated breathing and gaze direction, looking at the audience, her hands, and the music.

Henri Maillardet

- Henri Maillardet, also Swiss watchmaker, built a boy robot in 1815 that could write script in both French and English and draw a variety of landscapes.
- The heart of the writing and drawing operation is actually a mechanical "read only memory" in the form of an array of disk cams rotating on a common shaft to drive the right hand of the figure.
- The cams are driven by a spring motor located at one end of the base that is coordinated with a second motor located at the other end.
- The information contained in the undulations of the selected set of cams is picked up by three cam followers linked to the doll's hand to produce the required left and right, up and down, and vertical movements.
- There are seven programmed designs from which to choose.

Feedback Control

- **Feedback:** continuous monitoring of the sensors and reacting to their changes.
- Feedback control = self-regulation
- Two kinds of feedback:
  - Positive
  - Negative
- The basis of control theory

Feedback Control

- Negative feedback acts to regulate the state/output of the system e.g.., if too high, turn down, if too low, turn up
  - thermostats, toilets, bodies, robots...
- Positive feedback acts to amplify the state/output of the system e.g.., the more there is, the more is added
  - lynch mobs, stock market, ant trails...

Uses of Feedback

- Invention of feedback as the first simple robotics
- The first example came from ancient Greek water systems (toilets)
- Forgotten and re-invented in the Renaissance for ovens/furnaces
- Really introduced in Watt's steam engine

Cybernetics

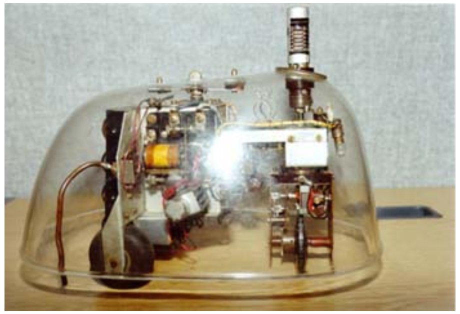
- Pioneered by Norbert Wiener (1940s) (From Greek "steersman" of steam engine)
- Marriage of control theory (feedback control), information science and biology
- Seeks principles common to animals and machines, especially for control and communication
- Coupling an organism and its environment (situatedness)

W. Grey Walter's Tortoise

- Machina Speculatrix
- Between Easter 1948 and Christmas 1949, Grey Walter built the first turtles, Elmer and Elsie. They had similar circuits and electronics, but their shells and motors were rather different.
- Although he demonstrated them in public in 1949 and 1950, they were rather unreliable and required frequent attention.
- In 1951, his technician, Mr. W.J. 'Bunny' Warren, designed and built six new turtles for Grey Walter; they were of a high professional standard.

Properties of the Turtle

- 1 photocell
- 1 bump sensor
- 1 motor



Behaviors

- seek light
- head to weak light
- back from bright light
- turn and push
- recharge battery
- Reactive control

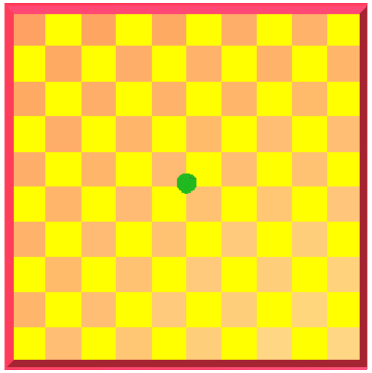
Turtle Principles

- **Parsimony**: simple is better (e.g.., clever recharging strategy)
- **Exploration/speculation**: keeps moving (except when charging)
- **Attraction** (positive tropism): motivation to approach light
- **Aversion** (negative tropism): motivation to avoid obstacles, slopes
- **Discernment**: ability to distinguish and make choices, i.e., to adapt

Braitenberg Vehicles

- Valentino Braitenberg (1984)
- Extended Walter's model in a series of thought experiments
- Also based on analog circuits
- Direct connections (excitatory or inhibitory) between light sensors and motors
- Complex behaviors from very simple mechanisms
- Reactive control
- Later implemented on real robots

Braitenberg Behaviors



- By varying the connections and their strengths, numerous behaviors result, e.g..:
  - "fear/cowardice" - flees light
  - "aggression" - charges into light
  - "love" - following/hugging
  - many others, up to memory and learning!

Vehicle 1: Alive

- **Components:** Sensor and motor.
- **Principle:** The more there is of the quality (e.g.., heat) to which the sensor is tuned, the faster the motor goes.
- **Description:** alive, restless, doesn't "like" heat

Vehicle 2a: Cowardly

- **Components:** 2 sensors, 2 motors, each sensor connected to the motor on the same side ("uncrossed")
- **Principle:** The more there is of the quality to which the sensor is tuned, the faster the motors go ("excitatory").
- **Description:** dislikes source to which the sensor is tuned; occasionally "attacks" it

Vehicle 2b: Aggressive

- **Components:** 2 sensors, 2 motors, each sensor connected to the motor on the opposite side ("crossed")
- **Principle:** The more there is of the quality to which the sensor is tuned, the faster the motors go ("excitatory").
- **Description:** dislikes source to which the sensor is tuned; "attacks" it

Vehicle 3a: Loving/Quietly Adoring

- **Components:** 2 sensors, 2 motors, each sensor connected to the motor on the same side ("uncrossed")
- **Principle:** The more there is of the quality to which the sensor is tuned, the slower the motors go ("inhibitory").
- **Description:** loves the source, wants to be near it, comes to rest facing it

Vehicle 3b: Loving/Exploring

- **Components**: 2 sensors, 2 motors, each sensor connected to the motor on the opposite side ("crossed")
- **Principle**: The more there is of the quality to which the sensor is tuned, the slower the motors go ("inhibitory").
- **Description**: likes the source, but easily attracted away

Vehicle 3c: Knowing, Valuing

- **Components**: 4 sensors, 4 motors, each tuned to different properties of the environment.
- **Principle**: one each of the four types so far:
  - uncrossed/excitatory: tuned to temperature
  - crossed/excitatory: tuned to light
  - uncrossed/inhibitory: tuned to organic material
  - crossed/inhibitory: tuned to oxygen level
- **Description:**
  - Cowardly toward areas of high temperature;
  - Aggressive toward light sources;
  - Loves organic material; leaves and seeks new source if environment is depleted;
  - Restlessly seeks best source of oxygen.
  - Vehicle 3c appears to know a great deal.

Vehicle 4a: Displaying Instincts, Specialization

- **Components**: sensors and motors
- **Principle**: connections both excitatory and inhibitory but non-monotonic
- **Description**: does everything 3c vehicles do, but with much less predictability.

Vehicle 4b: Making Decisions

- **Components**: sensors and motors, and threshold devices
- **Principle**: connections both excitatory and inhibitory but non-monotonic
- **Description**: does everything 3c vehicles do, but with much less predictability, and appears to ponder over its "decisions"; appears to will.

Vehicle 5: Reasoning Logically, Counting, Recognizing Individuals

- **Components**: sensors, motors, threshold devices, some networked, so they give output according to some numerical formula (e.g.., one out for every three in).
- **Principle**: connections are both excitatory and inhibitory, monotonic and non-monotonic. Like a computer.
- **Description:** apparently recognizes individuals, counts, does logic, math calculations.
- **Law of Uphill Analysis and Downhill Invention:** machines are easy to understand if you're creating them; much harder to understand "from the outside".
- **Psychological consequence:** if we don't know the internal structure of a machine, we tend to *overestimate* its complexity.

Vehicle 6: Evolving

- **Description** (from the outside): "the [mistaken] feeling of a mysterious supernatural hand guiding the creation"

Vehicle 7: Associating Ideas, Abstracting Concepts

- **Components**: sensors, motors, threshold devices, networks of threshold devices, and Mnemotrix wires between threshold devices.
- **Principle**:
  - simultaneous activation of both ends of Mnemotrix temporarily lowers resistance to stimuli at either end;
  - makes vehicle both more sensitive to this combination of environmental stimuli, and to the combined individuals alone. E.g., if aggressive predators are red in color, vehicle responds to other red things as if they were predators too.
- **Description:** Vehicle adjusts to new conditions, appears to derive concepts by abstraction from particular cases (e.g.., danger, "smell of death") – a capacity non-sentient beings were thought not to have!

Vehicle 8: Neighborhood, Thing-ness, Reality and Unreality, A priori concepts

- **Components**: all of above plus object detectors and movement/directionality detectors (connect threshold devices one-to-one with photo cells) – creating internal maps – plus lateral inhibition.
- **Principle**: lateral inhibition means an active threshold device automatically puts an brake on the activity of its neighbors, so the more it's activated, the more its neighbors are inhibited. (Vehicle appears to concentrate, focus.)
- **Description:**
  - Vehicle 8 behaves as though it understands the concept of space, e.g.., will take the diagonal to go back to a place it likes, even if it didn't arrive that way.
  - Vehicle 8's internal maps determine its concept of reality: e.g.., since it can't represent objects that are not physically contiguous in space through time, such objects can't be real. Solids objects cast continuous and regular shadows; don't change their shapes as they move, etc. Vehicle 8 "just knows" these things.

Vehicle 9: More a priori concepts; "Thou"; Confrontation; Properties of shapes

- **Components**: all of above plus bilateral symmetry, radial symmetry, periodicity detectors.
- **Principle**: A bilateral or radial symmetry detector is an array of threshold devices activated just when the vehicle is presented with a bilaterally or radially symmetrical object.
- **Descriptions**: Vehicle 9 appears able to "confront" others; has concept of the Other, which affects its behavior; has concept of being the focus of someone else's attention.

Vehicle 10: Getting More Complicated Ideas by Association

- **Components**: Mnemotrix devices with all features of Vehicle 9. These devices have been around awhile and have accumulated a lot of connections.
- **Principle**: Vehicle sees same string of stimuli many times, learns to associate all the elements of the string by process of association as in Vehicle 7.
- **Description**: Vehicle 10 behaves as though it has foresight, thinks.

Vehicle 11: Sequential Reasoning; Causes and Effects; Signals

- **Components**: all of above plus Ergotrix connections.
- **Principle**: Ergotrix conducts in one direction only and "has an increased conductance when it is interposed between elements that are active in succession within a brief period of time".

Vehicle 11: Sequential Reasoning; Causes and Effects; Signals

- Mnemotrix suited for acquiring descriptive knowledge.
- Ergotrix suited for acquiring dynamic knowledge.
- Both kinds of knowledge are essential to each other: reliable knowledge about interaction depends on good description; and vice-versa.
- Example: "Hear the lion's roar associated with see the lion" becomes "lion's roar caused by nearby lion". "Hear lion roar" becomes signal to run away.

Vehicle 12: Trains of Thought; Free Will

- **Components**: all of above plus "epilepsy inhibitor" – a threshold control device.
- **Principle**: A global negative feedback loop, that simultaneously raises or lowers all thresholds at once. Raising threshold of outside stimuli --> more attention can be directed "inward" --> possibility of "trains of thought".
- For any fairly large brain, each configuration of active elements will be unpredictable based on the previous configuration; i.e., the vehicle's thoughts can surprise itself as well as predators (evolutionary advantage).

Vehicle 13: Genuine Foresight; Intentionality, Individuation

- **Components**: all the above plus splitting brain into two halves (predictor and sensor).
- **Principle**:
  - Compare expectations (formed by Ergotrix and Mnemotrix) with sensory input. Incorporate rule: When in doubt, believe sensors.
  - Make the Predictor more and more accurate by a new component, faster Ergotrix (short-term memory), which can serve as a "mental echo", and note Darwinian survival knowledge (the "Darwinian evaluator" mechanism D).

Vehicle 13: Genuine Foresight; Intentionality, Individuation

- "Whenever the Darwinian evaluator D signals an unpleasant turn in the real course of events, or a very pleasant one, the predicting half-brain P is disconnected from the input it normally receives from the realistic (sensory) half-brain, R.
- Instead the predicting half-brain receives its input from the short-term memory two steps back. So it will go again through the two instants preceding the important happening.

Vehicle 13: Genuine Foresight; Intentionality, Individuation

- At the same time its output is connected to the input of the short-term memory. So it will receive over and over again via the short-term memory the succession of the two events, a and b, until the Darwinian evaluator D has calmed down and everything has switched back to normal. The net effect is that strings of events leading to strongly emotional consequences are incorporated strongly into the Mnemotrix-Ergotrix system even if they occur only rarely." (78)
- **Description**: Vehicles of type 13 appear individuated – they will be quite different one from another because they've had different experiences.

Vehicle 14: Egoism and Optimism

- **Components**: all the above, plus incorporate a new principle that favors optimism.
- **Principle** (new): When choosing among several equally likely next brain states, choose the most pleasant one.
- **Description**: Vehicles of type 14 "dream", and "run after their dreams". "They move through their world with consistent determination," guided by a chain of optimistic predictions, which often turn out to make the state of the world a "more favorable" one.

Trends in Robotics

Classical Robotics (mid-70's)
• exact models
• no sensing necessary

Reactive Paradigm (mid-80's)
• no models
• relies heavily on good sensing

Hybrids (since 90's)
• model-based at higher levels
• reactive at lower levels

Probabilistic Robotics (since mid-90's)
• seamless integration of models and sensing
• inaccurate models, inaccurate sensors

Early Artificial Intelligence

- "Born" in 1955 at Dartmouth
- "Intelligent machine" would use internal models to search for solutions and then try them out (M. Minsky) => deliberative model!
- Planning became the tradition
- Explicit symbolic representations
- Hierarchical system organization
- Sequential execution

Artificial Intelligence (AI)

- Early AI had a strong impact on early robotics
- Focused on knowledge, internal models, and reasoning/planning
- Eventually robotics developed more appropriate approaches => behavior-based and hybrid control
- AI itself has also evolved...
- But before that, early robots used deliberative control

Industrial Use

- Robot Manipulators
  - Robot arms were introduced to industries in 1956 by Unimation
- Automated Guided Vehicles (AGV)

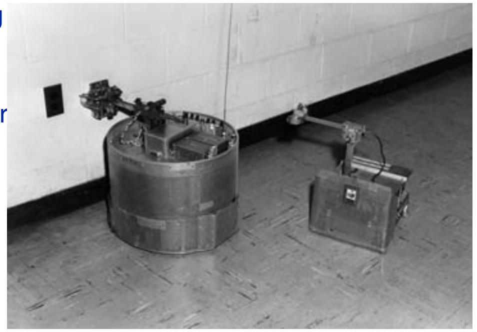
Manipulators

Configuration of robot specified by numbers
degrees of freedom (DOF)

6 is the minimum number required to position end-efl
For dynamical systems, add velocity for each DOF.

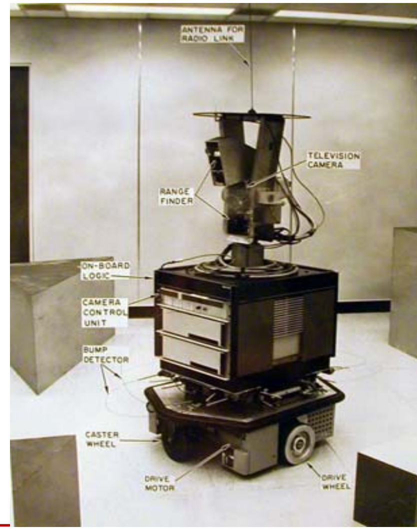
Early Robots: Hopkins Beasts

- These machines wandered hallways guided by sonar and found sockets by feeling along walls.
- In subsequent work, the larger unit was given another layer containing a photocell circuit that allowed it to find contrasting wall plugs optically from a distance.



Early Robots: SHAKEY

- Shakey (1970) had
  - a TV camera,
  - a triangulating range finder,
  - bump sensors,
  - was connected to DEC PDP-10 and PDP-15 computers via radio and video links.

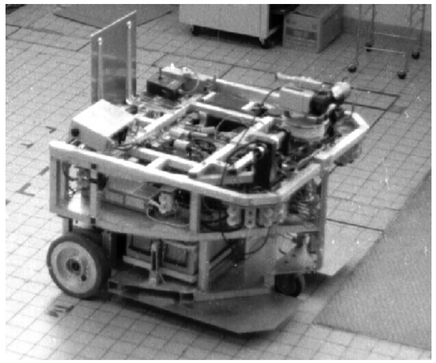


Early Robots: SHAKEY

- 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 make and execute plans to achieve goals given it by a user.
  - The system also generalized and saved these plans for possible future use.

Early Robots: HILARE

- LAAS in Toulouse, France (1977)
- Video, ultrasound, laser range-finder
- Still in use (as a table support)!
- Multi-level spatial representations
- Deliberative -> Hybrid Control

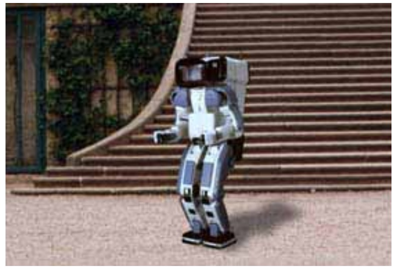


Early Robots: CART/Rover

- Hans Moravec
- Stanford Cart (1977) followed by CMU rover (1983)
- Sonar and vision
- Deliberative control

Robotics Today

- Assembly and manufacturing (most numbers of robots, least autonomous)
- Materials handling
- Gophers (hospitals, security guards)
- Hazardous environments (Chernobyl)
- Remote environments (Pathfinder)
- Surgery (open heart, brain, hips)
- Tele-presence and virtual reality
- Entertainment



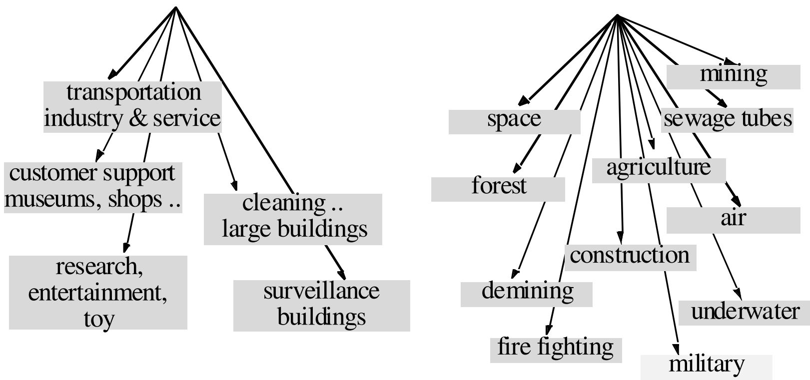
Applications of Mobile Robots

Indoor

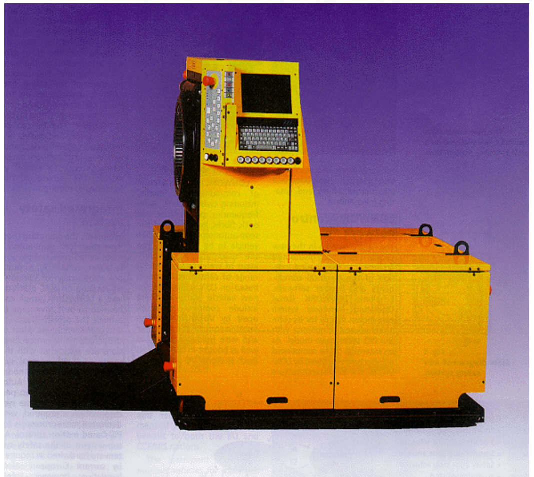
Structured Environments

Outdoor

Unstructured Environments

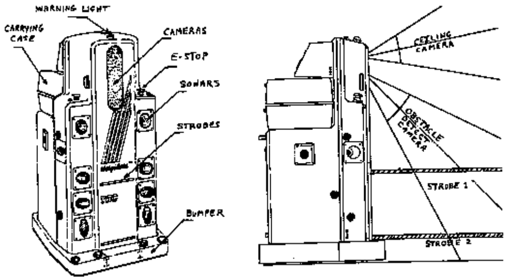


Automatic Guided Vehicles



- Newest generation of Automatic Guided Vehicle of VOLVO used to transport motor blocks from on assembly station to an other. It is guided by an electrical wire installed in the floor but it is also able to leave the wire to avoid obstacles. There are over 4000 AGV only at VOLVO's plants.

Helpmate

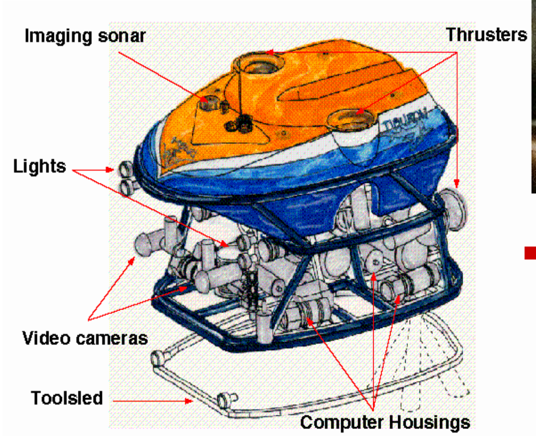


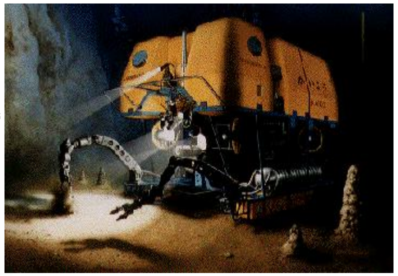
- HELPMATE is a mobile robot used in hospitals for transportation tasks. It has various on board sensors for autonomous navigation in the corridors. The main sensor for localization is a camera looking to the ceiling. It can detect the lamps on the ceiling as reference (landmark). http://www.ntplx.net/~helpmate/

BR700 Cleaning Robot

- BR 700 cleaning robot developed and sold by Kärcher Inc., Germany. Its navigation system is based on a very sophisticated sonar system and a gyro. http://www.kaercher.de

ROV Tiburon Underwater Robot





- Picture of robot ROV Tiburon for underwater archaeology (teleoperated)- used by MBARI for deep-sea research, this UAV provides autonomous hovering capabilities for the human operator.

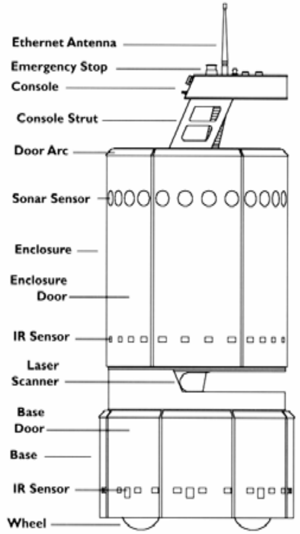
The Pioneer

- Picture of Pioneer, the teleoperated robot that is supposed to explore the Sarcophagus at Chernobyl

The Pioneer

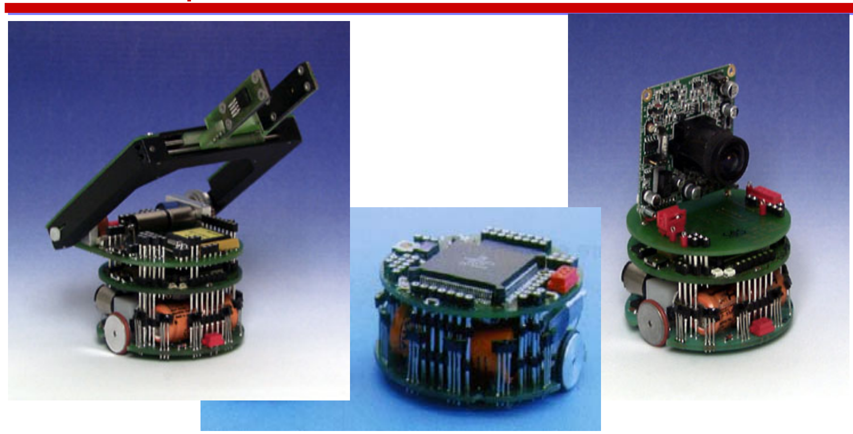

- PIONEER 1 is a modular mobile robot offering various options like a gripper or an on board camera. It is equipped with a sophisticated navigation library developed at Stanford Research Institute (SRI). http://www.activmedia.com/robots

The B21 Robot



- B21 of Real World Interface is a sophisticated mobile robot with up to three Intel Pentium processors on board. It has all different kinds of on board sensors for high performance navigation tasks. http://www.rwii.com

The Khepera Robot

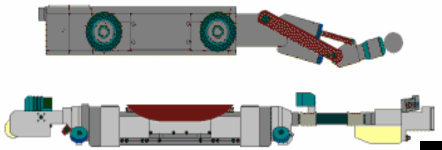


- KHEPERA is a small mobile robot for research and education. It sizes only about 60 mm in diameter. Additional modules with cameras, grippers and much more are available. More then 700 units have already been sold (end of 1998). http://diwww.epfl.ch/lami/robots/K-family/ K-Team.html

Forester Robot

- Pulstech developed the first ‘industrial like’ walking robot. It is designed moving wood out of the forest. The leg coordination is automated, but navigation is still done by the human operator on the robot. http://www.plustech.fi/

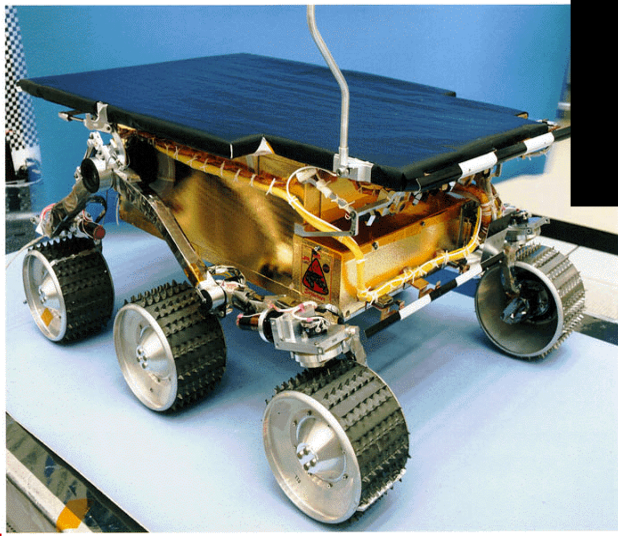
Robots for Tube Inspection



- HÄCHER robots for sewage tube inspection and reparation. These systems are still fully teleoperated. http://www.haechler.ch

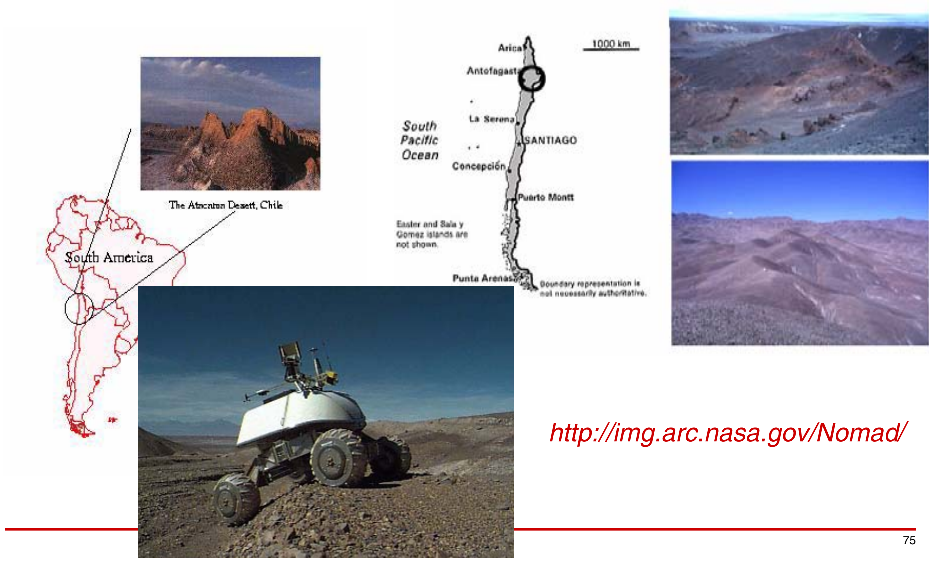
- EPFL / SEDIREP: Ventilation inspection robot

Sojourner, First Robot on Mar



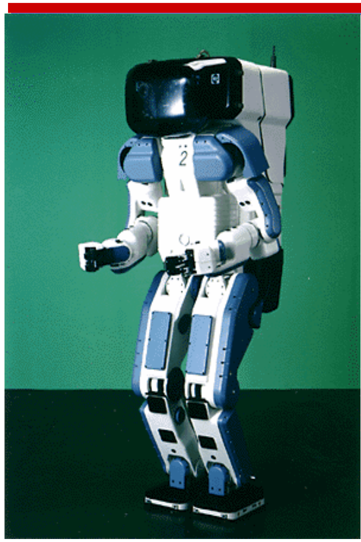
Pathfinder mission to explore the mars in summer 1997. It was nearly fully teleoperated from earth. However, some on board sensors allowed for obstacle detection. http://ranier.oact.hq.nasa.gov/telerobotics_page/telerobotics.shtm

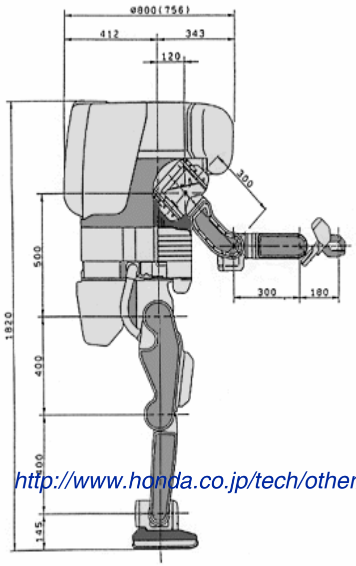
NOMAD, Carnegie Mellon / NASA



http://img.arc.nasa.gov/Nomad/

The Honda Walking Robot





http://www.honda.co.jp/tech/other/robot.html

Entertainment Robot Aibo from Sony

- Size
  - length about 25 cm
- Sensors
  - color camera
  - stereo microphone
- Discontinued in March 2006

Components of a Robot

- sensors
- effectors/actuators
- locomotion system
- on-board computer system
  - contains the controllers for all of the above

Typical Mobile Robot Components

- A sensor set:
  - Sonars, which use sound to measure the positions of objects
  - Infrared proximity detectors, which use light to test the presence of objects
  - Video cameras, which can be used for a number of different tasks
  - Bump switches and other tactile sensors that report the forces exerted on the robot by the objects around it.

Sensors

- Range finders: sonar (land, underwater), laser range finder, radar (aircraft), tactile sensors, GPS

- Imaging sensors: cameras (visual, infrared)
- Proprioceptive sensors: shaft decoders (joints, wheels), inertial sensors,force sensors, torque sensors

Sensor Set

- Shaft encoders, which measure the rotation of a wheel or motor shaft like the odometer of a car. This information can be used to measure velocity or to compute position using dead reckoning.
- Pyro-electric motion sensors which report the presence of a moving heat source, such as a human.

Typical Mobile Robot Components

- A set of Effectors
  - wheels,
  - legs, and
  - arms,
  - speakers (for making sounds),
  - dispensers for various materials, etc.
- A power supply (typically a set of rechargeable batteries)
- One or more computers, for connecting the sensors to the effectors,
- A body for holding it all together.

Sensing

- What can be sensed?
  - depends on the sensors on the robot
  - the robot exists in its sensor space (i.e., all possible values of its sensory readings, also called perceptual space)
  - robotic sensors are very different from biological sensors;
- What needs to be sensed?
  - depends on the robot's task

Sensors

- Sensors for Deadreckoning
  - Optical Encoders
  - Doppler Sensors
- Heading Sensors
  - Mechanical Gyroscopes
  - Piezoelectric Gyroscopes
  - Optical Gyroscopes
  - Geomagnetic Sensors

Sensors II

- Ground-Based RF Beacons
- GPS
- Sensors for Map-Based Positioning
  - Time-of-Flight Sensors
  - Phase-Shift Measurement
  - Frequency Modulation

Definition of State

- State: a sufficient description of the system
  - observable: the robot knows its state at all times
  - hidden/inaccessible/unobservable: the robot does not know its state
  - partially-observable: the robot knows some part of its state
  - Discrete (e.g., up, down, blue, red) or continuous (e.g.., 3.765 mph)

State Space

- State space: all the states a system can be in
  - External state: state of the world
    night/day, raining/sunny, at home, etc.
    sensed using the robot's sensors
  - Internal state: state of the robot
    - happy/sad, stalled/moving, battery level, velocity, etc.
    - can be sensed (e.g.., velocity)
    - can be stored/remembered (e.g.., happy/sad)
  - The robot's state is a combination of its external and internal state.

Internal States/Models

- Internal state can be used to remember information about the world (e.g.., remember paths to the goal, remember maps, remember friends or enemies, etc.)
- This is called a representation or an internal model.
- Representations/models have a direct influence the complexity of the controller.

Acting

- 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)
- This divides robotics into two areas
  - mobile robotics
  - manipulator robotics

Action vs. Behavior

- Behavior is what an external observer sees a robot doing.
- Robots are programmed to display desired behavior.
- Behavior is a result of a sequence of robot actions.
- Observing behavior may not tell us much about the internal control of a robot.
- Control can be a black box.

Mobile Robots

- Mobile robots can move around, using wheels, tracks, or legs, and usually move in 2-dimensions;
- however, swimming and flying robots are also mobile robots, and they move in 3-dimensions (and are therefore even harder to control)

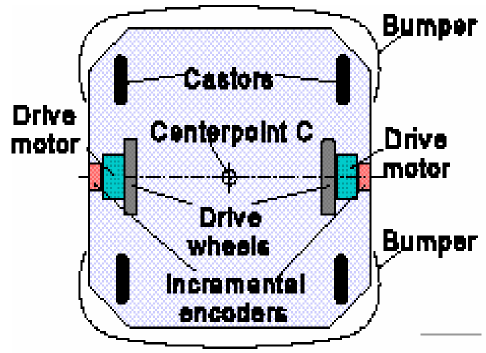
Manipulators

- Manipulators are various robot arms; they can move in 1 or more dimensions.
- The number of dimensions are called the robot's degrees of freedom (DOF).

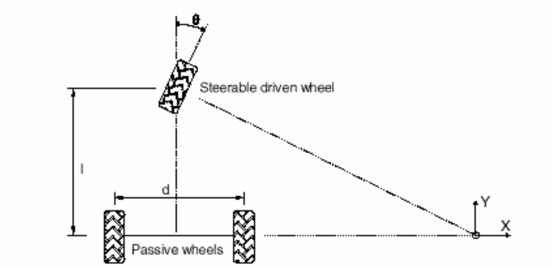
Actuators

- AC motors
- DC motors
  - Servomotors
  - Stepper motors

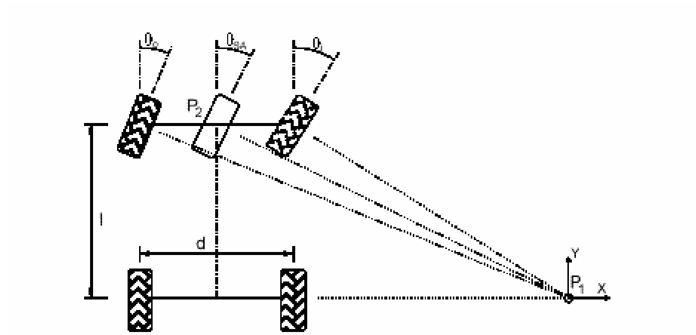
Differential Drive



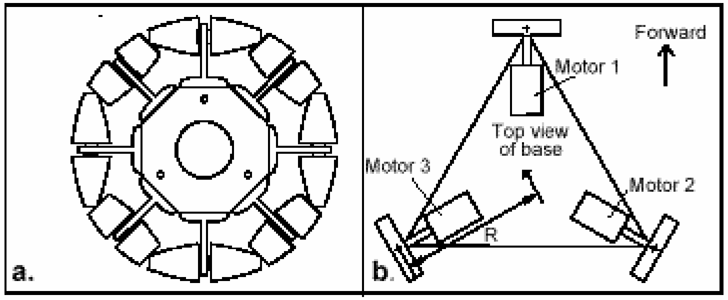
Tricycle Device



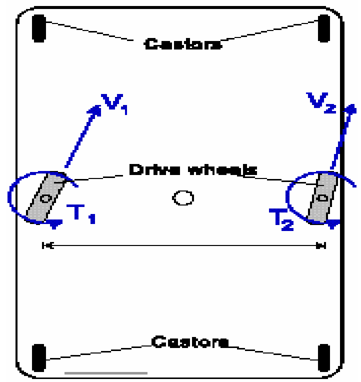
Ackerman Steering



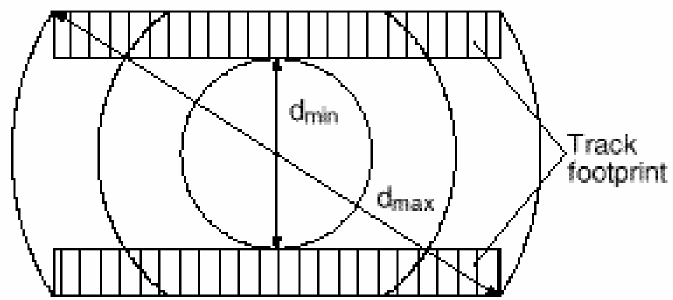
Omnidirectional Drive



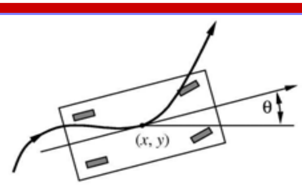
Multi-Degree of Freedom Vehicles



Tracked Vehicles

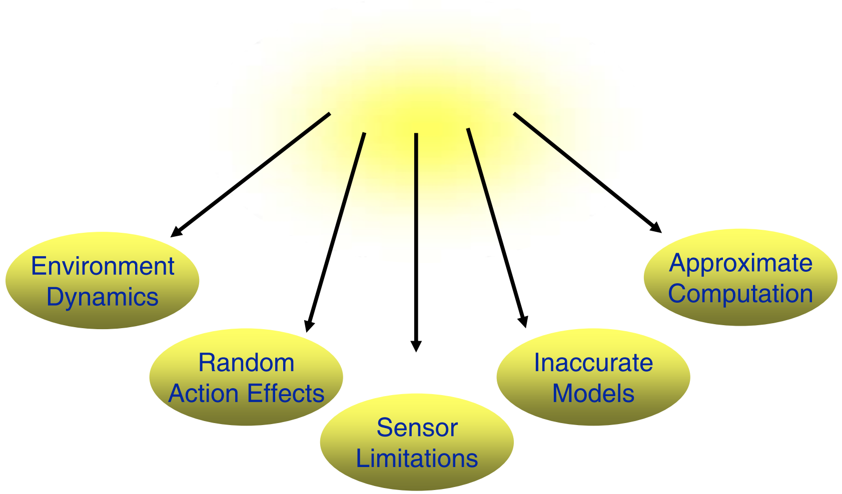


Non-holonomic robots

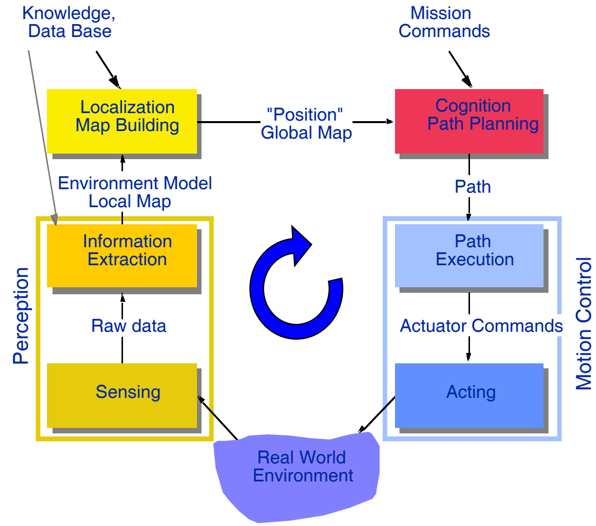


A car has more DOF (3) than controls (2), so is non-holonomic;
cannot generally transition between two infinitesimally close configurations

Five Sources of Uncertainty

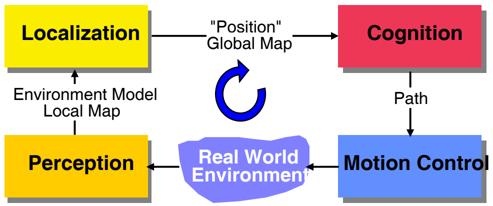


General Control Scheme for Mobile Robot Systems

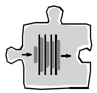


Control Architectures / Strategies

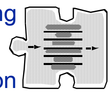
- Control Loop
  - **dynamically changing**
  - **no compact model available**
  - **many sources of uncertainty**



- Two Approaches
  - Classical AI
    - complete modeling
    - function based
    - horizontal decomposition

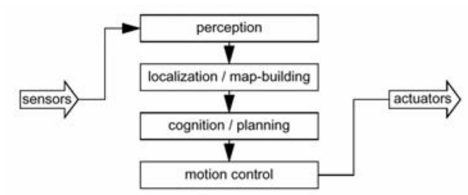


  - New AI, AL
    - sparse or no modeling
    - behavior based
    - vertical decomposition
    - bottom up

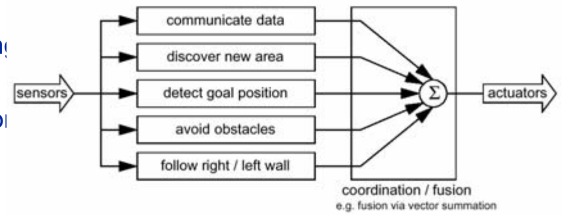


Two Approaches

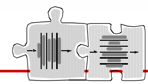
- Classical AI
  (model based navigation)
  - complete modeling
  - function based
  - horizontal decomposition



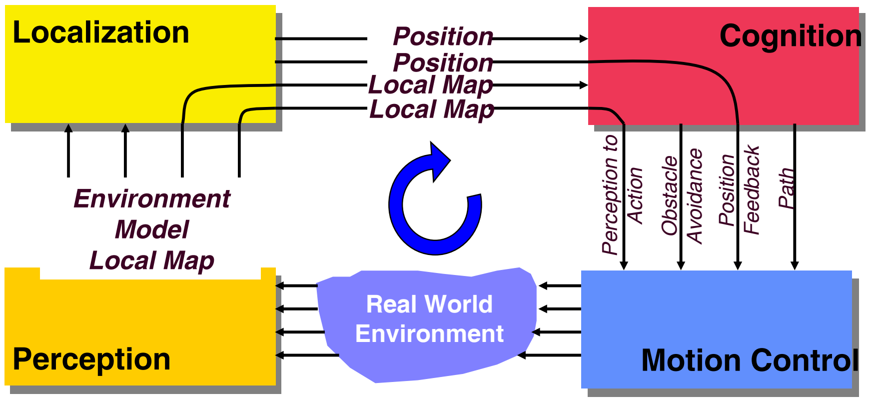
- New AI, AL
  (behavior based navigation)
  - sparse or no modeling
  - behavior based
  - vertical decomposition
  - bottom up



- Possible Solution
  - Combine Approaches



Mixed Approach Depicted into the General Control Scheme

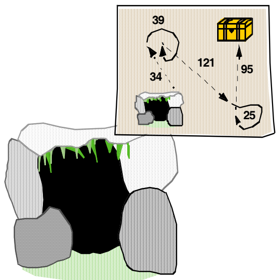


Environment Representation and Modeling:
The Key for Autonomous Navigation

- Environment Representation
  - Continuos Metric -> x,y,θ
  - Discrete Metric -> metric grid
  - Discrete Topological -> topological grid
- Environment Modeling
  - Raw sensor data, e.g. laser range data, grayscale images
    - large volume of data, low distinctiveness
    - makes use of all acquired information
  - Low level features, e.g. line other geometric features
    - medium volume of data, average distinctiveness
    - filters out the useful information, still ambiguities
  - High level features, e.g. doors, a car, the Eiffel tower
    - low volume of data, high distinctiveness
    - filters out the useful information, few/no ambiguities, not enough information

Environment Representation and Modeling: How we do it!

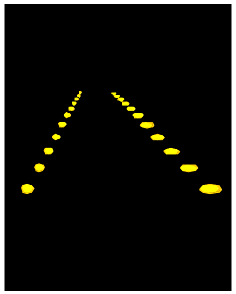
- Odometry



How to find a treasure

  - not applicable

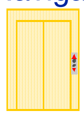
- Modified Environments



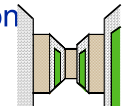
Landing at night

  - expensive, inflexible

- Feature-based Navigation

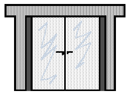


Elevator door



Corridor crossing

Eiffel Tower



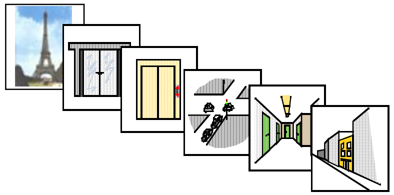
Entrance

  - still a challenge for artificial systems

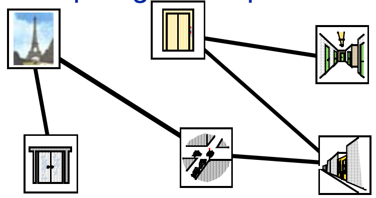
Courtesy K. Arras

Environment Representation: The Map Categories

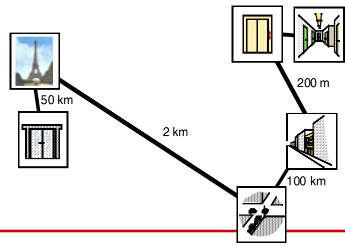
- Recognizable Locations



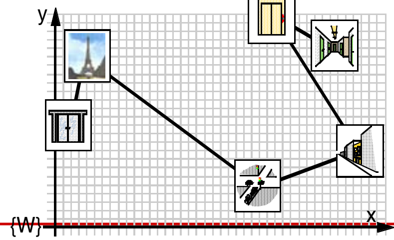
- Topological Maps



- Metric Topological Maps



- Fully Metric Maps (continuos or discrete)



Courtesy K. Arras

Environment Models: Continuous <-> Discrete ; Raw data <-> Features

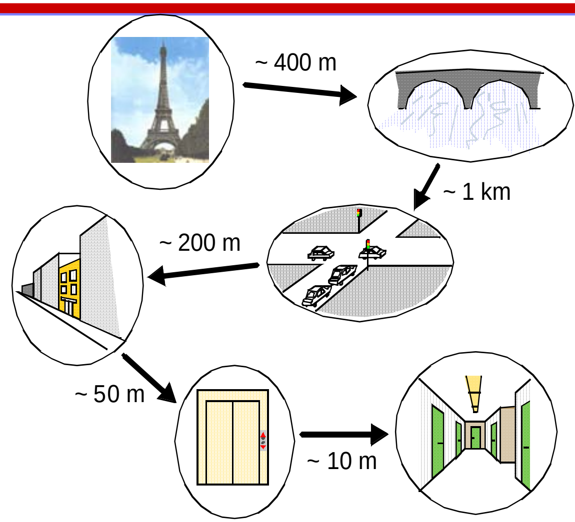
- **Continuos**
  - **position in x,y,θ**
- **Discrete**
  - **metric grid**
  - **topological grid**

- **Raw Data**
  - **as perceived by sensor**
- **A feature** (or natural landmark) is an environmental structure which is static, always perceptible with the current sensor system and locally unique.

Examples

- geometric elements (lines, walls, column ..)
- *a railway station*
- *a river*
- *the Eiffel Tower*
- *a human being*
- *fixed stars*
- *skyscraper*

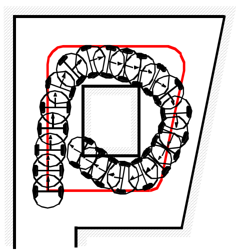
Human Navigation: Topological with imprecise metric information



Courtesy K. Arras

Methods for Navigation: Approaches with Limitations

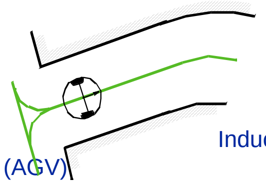
- Incrementally
  (dead reckoning)



Odometric or initial sensors (gyro)

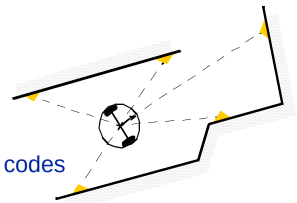
- **not applicable**

- Modifying the environments
  (artificial landmarks / beacons)



(AGV)

Inductive or optical tracks



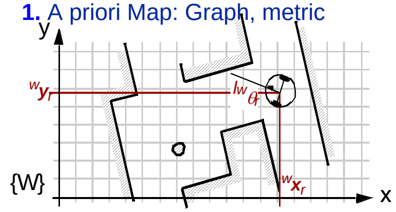
Reflectors or bar codes

- **expensive, inflexible**

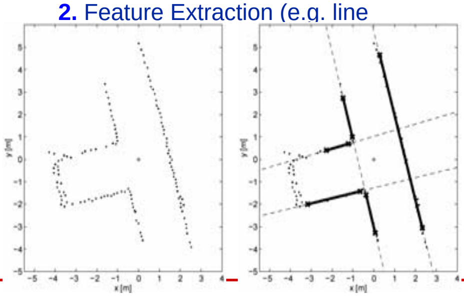
Courtesy K. Arras

Methods for Localization: The Quantitative Metric Approach

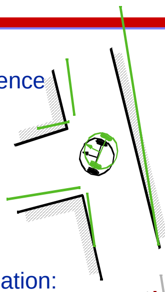
1. A priori Map: Graph, metric



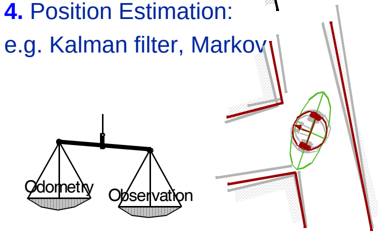
2. Feature Extraction (e.g. line



3. Matching:
Find correspondence of features



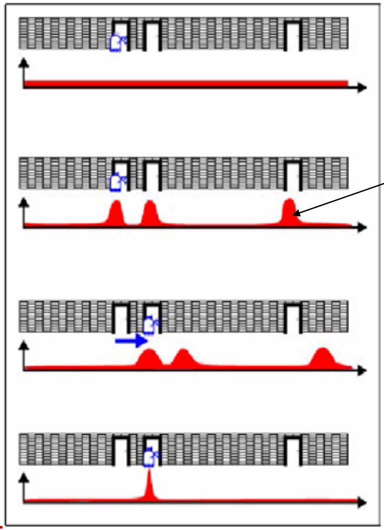
4. Position Estimation:
e.g. Kalman filter, Markov



- representation of uncertainties
- optimal weighting acc. to a priori statistics

Courtesy K. Arras

Gaining Information through motion: (Multi-hypotheses tracking)

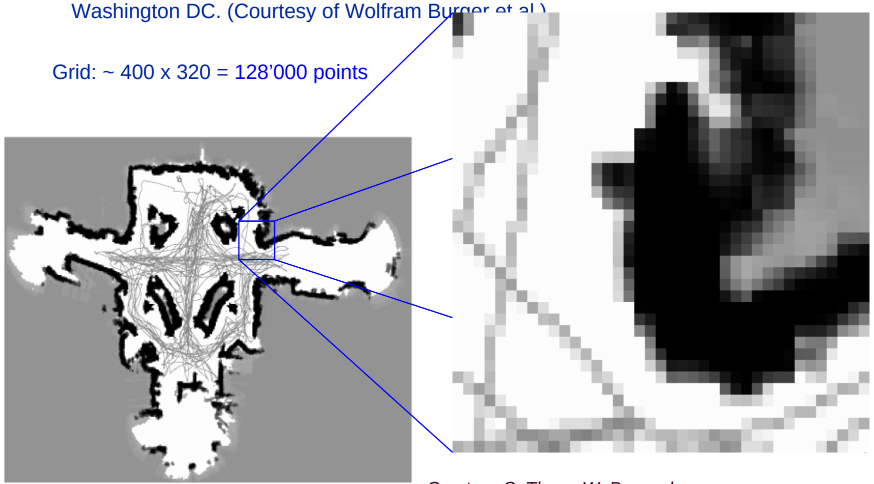


Courtesy S. Thrun, W. Burgard

Grid-Based Metric Approach

- Grid Map of the Smithsonian's National Museum of American History in Washington DC. (Courtesy of Wolfram Burger et al.)

Grid: ~ 400 x 320 = 128'000 points



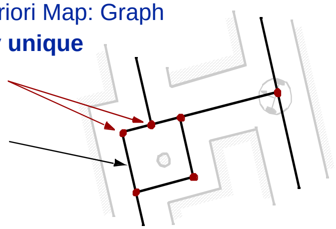
Courtesy S. Thrun, W. Burgard

Methods for Localization: The Quantitative Topological Approach

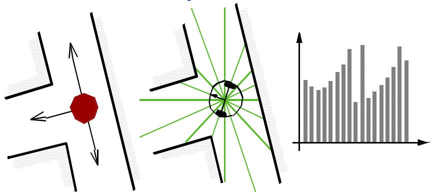
1. A priori Map: Graph

locally **unique** points

edges



2. Method for determining the **local uniqueness**

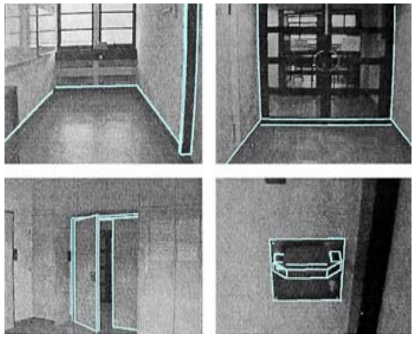


e.g. striking changes on raw data level or highly distinctive features

3. Library of **driving behaviors**

e.g. wall or midline following, blind step, enter door, application specific behaviors

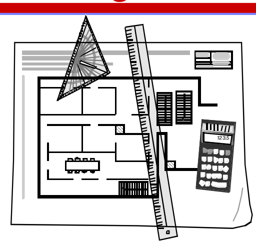
Example: Video-based navigation with natural landmarks



Courtesy of [Lanser et al. 1996]

Map Building: How to Establish a Map

1. By Hand



2. Automatically: **Map Building**

The robot **learns** its environment

Motivation:
- by hand: hard and costly
- dynamically changing environment
- different look due to different perception

3. Basic Requirements of a Map:
- a way to incorporate newly sensed information into the existing world model
- information and procedures for estimating the robot's position
- information to do path planning and other navigation task (e.g. obstacle avoidance)

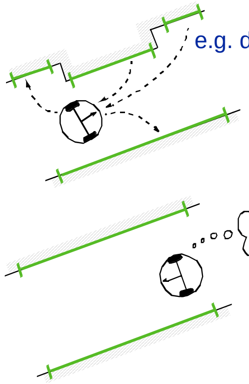
predictability

- Measure of Quality of a map
  - topological correctness
  - metrical correctness
- But: Most environments are a mixture of predictable and unpredictable features
  → hybrid approach
  model-based vs. behaviour-based

Courtesy K. Arras

Map Building: The Problems

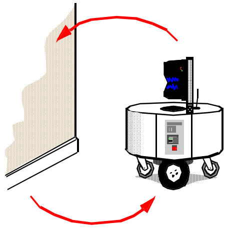
1. Map Maintaining: Keeping track of changes in the environment



- e.g. measure of belief of each environment feature

2. Representation and Reduction of Uncertainty

position of robot -> position of wall



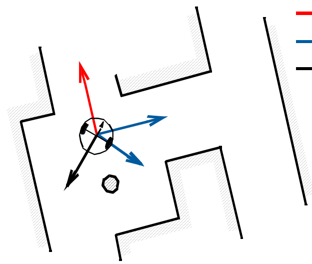
position of wall -> position of robot

- probability densities for feature positions
- additional exploration strategies

Courtesy K. Arras

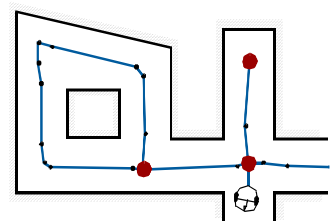
Map Building: Exploration and Graph Construction

1. Exploration



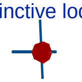
- provides correct topology
- must recognize already visited location
- backtracking for unexplored openings

2. Graph Construction



Where to put the nodes?

- Topology-based: at distinctive locations

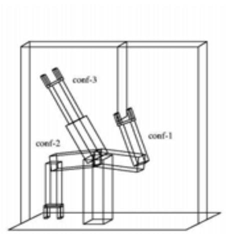


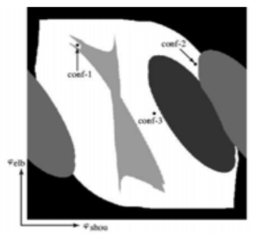
- Metric-based: where features disappear or get visible

Courtesy K. Arras

Motion Planning

- Idea: plan in configuration space defined by the robot's DOFs



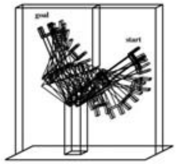


- Solution is a point trajectory in free C-space

Configuration space planning

- Basic problem: ∞^d states!
- Convert to finite state space.
  - Cell decomposition:
    - divide up space into simple cells,
    - each of which can be traversed "easily" (e.g., convex)
  - Skeletonization:
    - identify finite number of easily connected points/lines that form a graph such that any two points are connected by a path on the graph

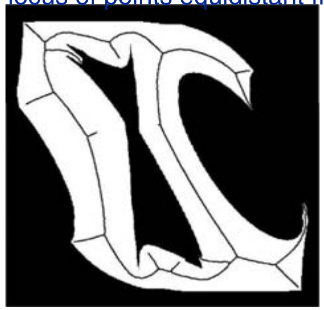
Cell decomposition example



- Problem: may be no path in pure freespace cells
- Solution: recursive decomposition of mixed (free+obstacle) cells

Skeletonization: Voronoi diagram

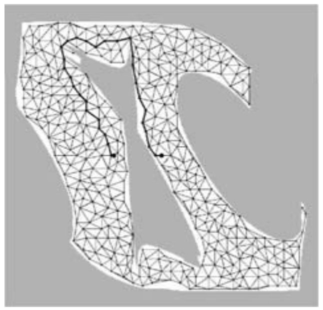
- Voronoi diagram: locus of points equidistant from obstacles



- Problem: doesn't scale well to higher dimensions

Skeletonization: Probabilistic Roadmap

- A probabilistic roadmap is generated by generating random points in C-space and keeping those in freespace; create graph by joining pairs by straight lines



- Problem: need to generate enough points to ensure that every start/goal pair is connected through the graph

Motor control

- Can view the motor control problem as a search problem in the dynamic rather than kinematic state space:
  - state space defined by x_1, x_2 , . . ., x_1, x_2
  - continuous, high-dimensional (Sarcos humanoid: 162 dimensions)
- Deterministic control: many problems are exactly solvable esp. if linear, low-dimensional, exactly known, observable
- Simple regulatory control laws are effective for specified motions
- Stochastic optimal control: very few problems exactly solvable => approximate/adaptive methods