Essentials of autonomous robotics

Book author: Henry Hexmoor
Slides author: Filip Matzner

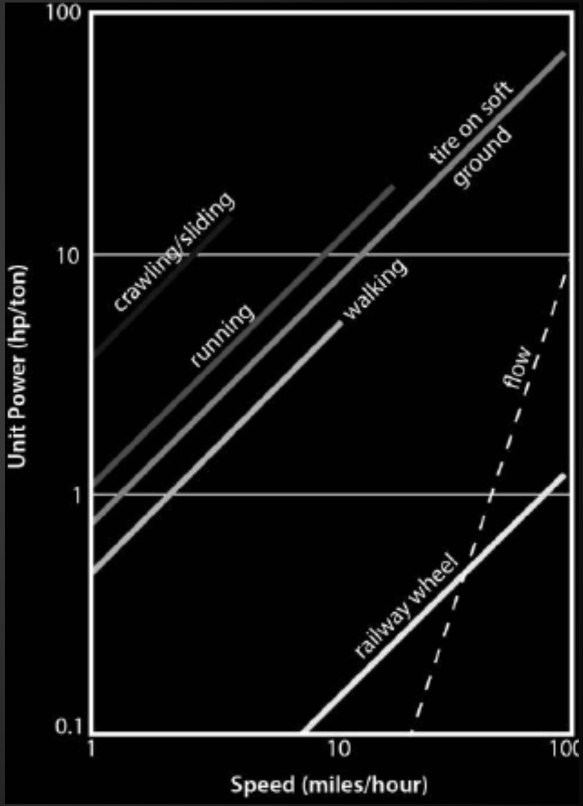
Part I: Preliminaries

Agency, Motion and Anatomy

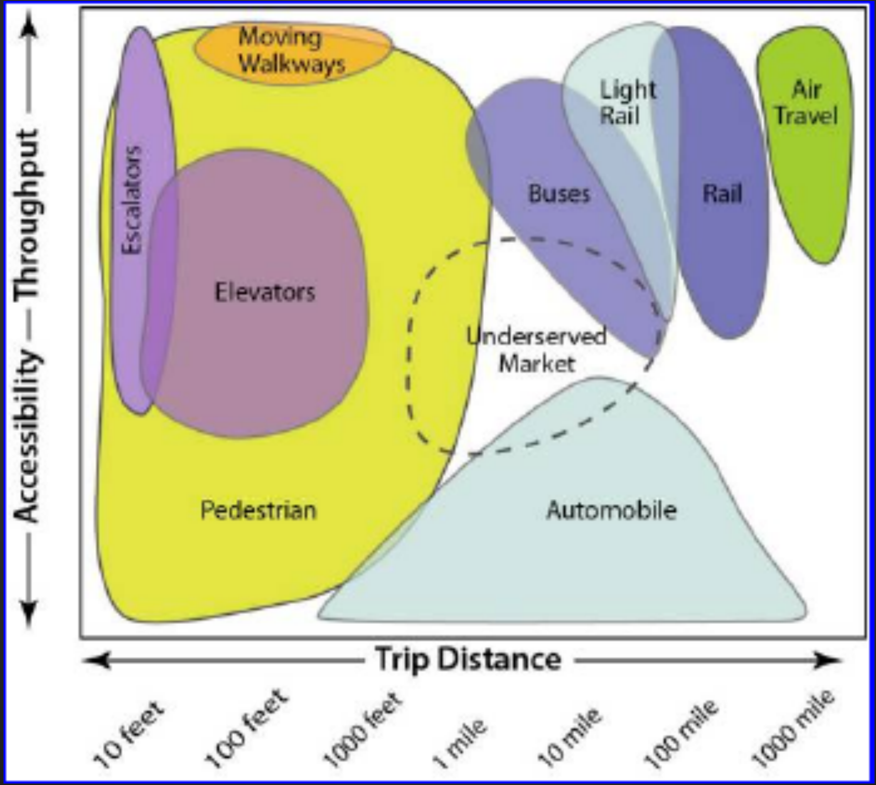
- the human race is improving their bodies and minds by technology
  - smartphones
  - prostheses
  - …
- the future might be full of silicone-based beings possessing biological prostheses and vice versa
- the difference between humans and machines fades
  - today’s problem: If Google car causes an accident, who is responsible?

Comparison of Motion Efficiency

- wheels
  - very efficient on hard ground, not as much on soft ground
  - requires few and simple actuators
- legs
  - does not lose efficiency on soft ground
  - difficult to build for engineers
  - easy to build for nature



Accessibility vs Throughput



Legged Robots

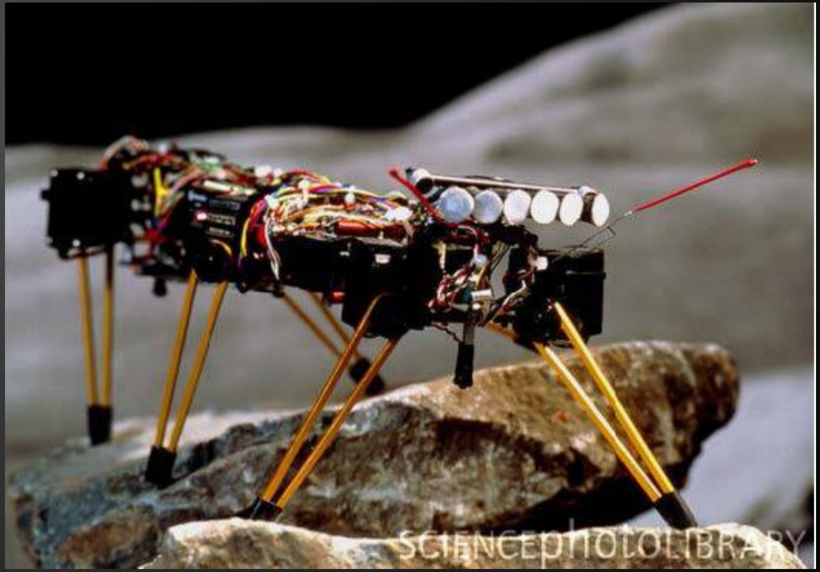
Aldebaran Nao

Robonaut (NASA)

Legged Robots

Alpha dog (Boston Dynamics)

Genghis (MIT)

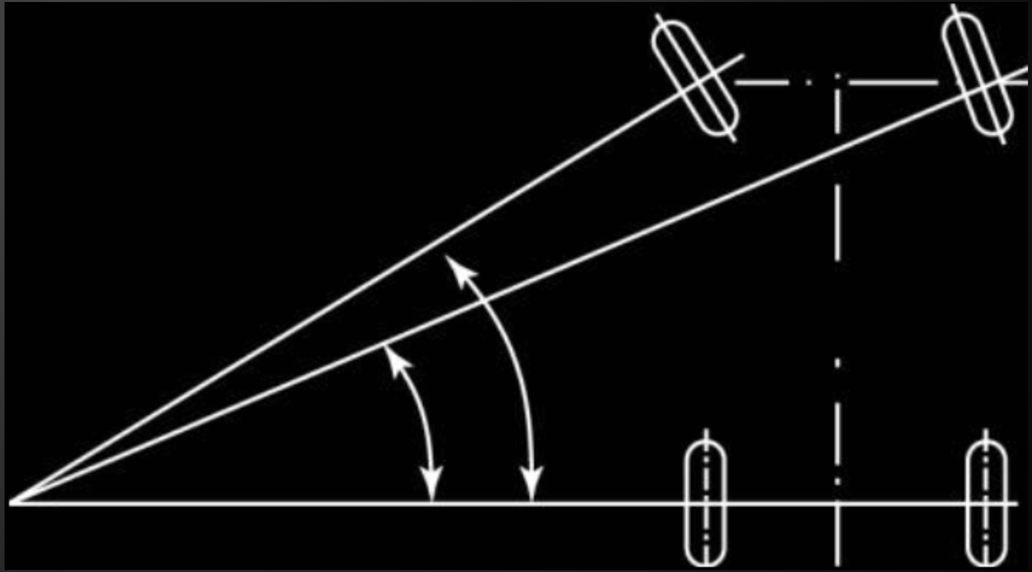


Wheeled Robots: Differential Drive

- wheels on both sides are separately and independently powered

Wheeled Robots: Ackerman Drive

- allows the inner turning wheel to turn at a larger angle than the outer turning wheel
- Ackerman is used in motor vehicles



Agency, Motion and Anatomy: Conclusion

- our fascination with biologically-inspired robots has led us to broad diversification
- there are robots using bird-like wings and robots which adapt to to locomotion without knowledge of their own anatomy

Behaviors

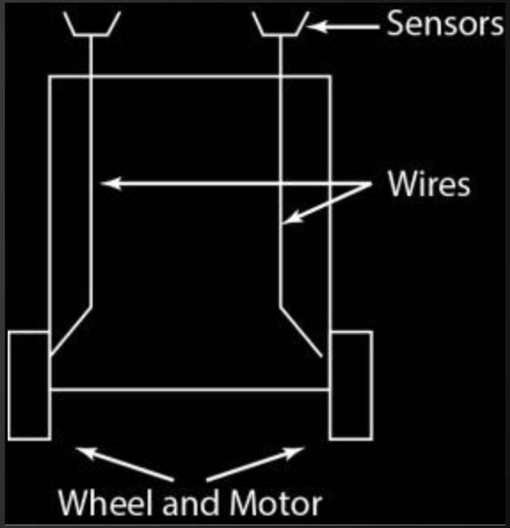
- behavior-based robotics
  - interactions of a robot in an environment are likened to a finite set of distinct self-contained animal behaviors
  - animal behavior is innate and instinctive
- selection is responsible for developing breeds with unique behavior
- example of instinctive behavior
  - all cows, everywhere, face north or south while eating
  - animals leave an area when they sense an earthquake

Behaviors

- simple behavior may have complex causes
  - A Braitenberg “Alive” vehicle
    - two light sensors connected to the motors
    - with connection to the motor

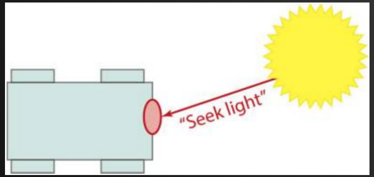
      on the same side, the vehicle prefers dark places
    - with connection to the motor

      on the other side, the vehicle prefers light places

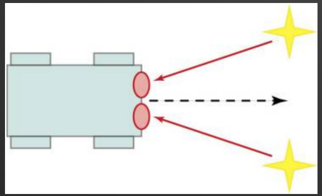


Common behavior types

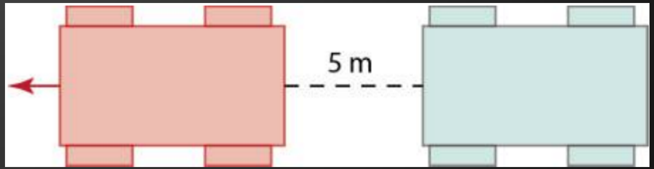
- reflexes
  - fast and involuntary movements
- threshold-based behavior
- taxis
  - instinctive tendency to approach or avoid particular stimulus
- tropotaxis
  - taxic behavior in which sensory inputs are compared
- condition-based taxis
  - maintain a condition during a response



taxis



tropotaxis



condition-based taxis

Common behavior types

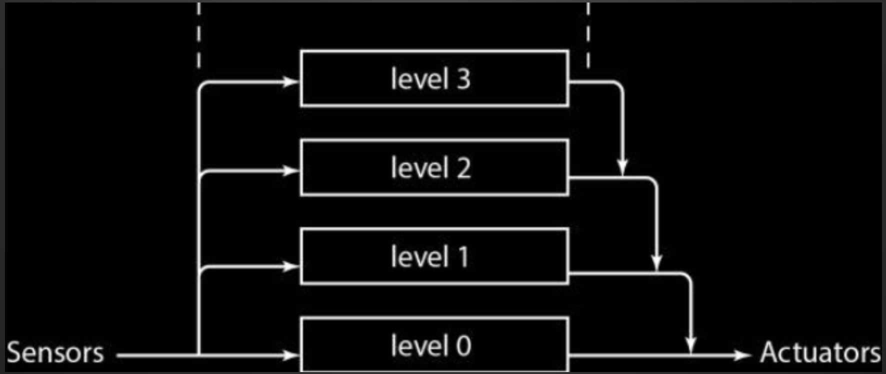
- swarming
  - emergent, collective behavior of decentralized, self-organized systems, natural or artificial

A flock of auklets

Symbrion project

Behaviors

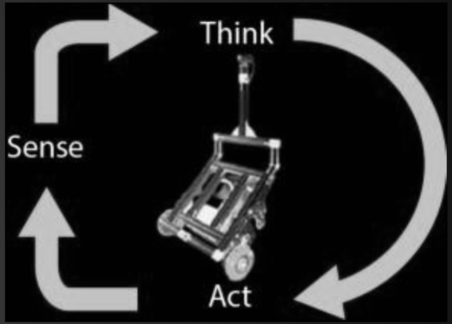
- an issue that arises is the need for organization among competing behaviors
- possible solution: subsumption architecture



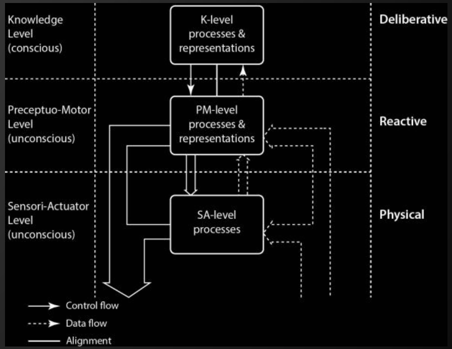
higher level subsumes lower levels

Architectures

- set of principles of robot behavior
- sense-think-act
  - traditional AI approach
  - borrows from human cognition
- subsumption architecture
  - replaced classic pipeline (horizontal) models
- 3T (three-tier) model
  - uses learning to migrate routine activities to higher levels
- RCS
  - under development in National Institute of Standards
  - perhaps the most complex



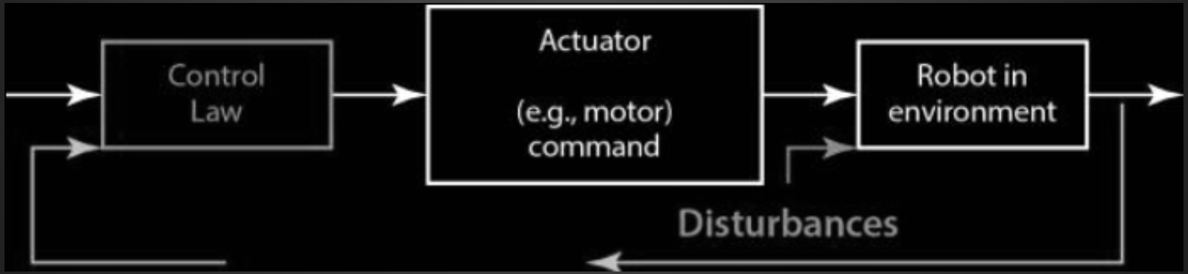
Sense-Think-Act



GLAIR 3T Architecture

Architectures

- feedback-loop
  - usually used at low-level control
  - e.g., PID controller

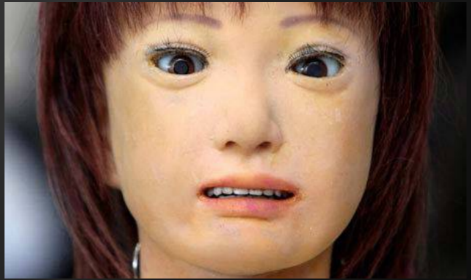


Affect

- phenomenon that manifests itself in the form of feelings
- “To be alive is to have feelings.”
- robots have to understand human emotions in order to improve human-robot cooperation
- humans often use emotions for decision making when there is an absence of rational motivation

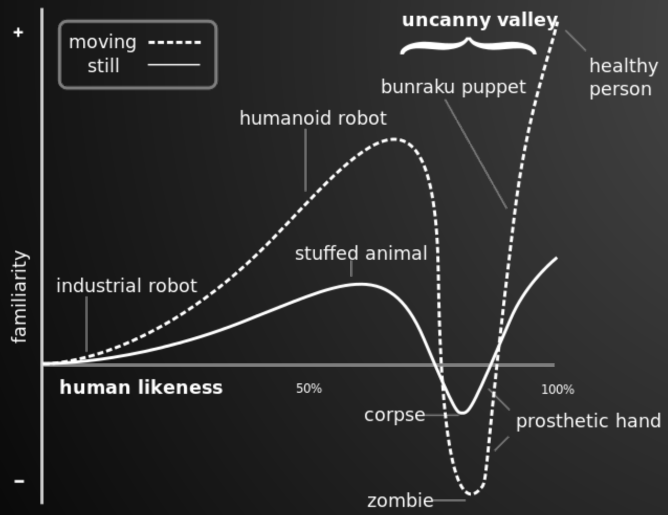
MIT Aida

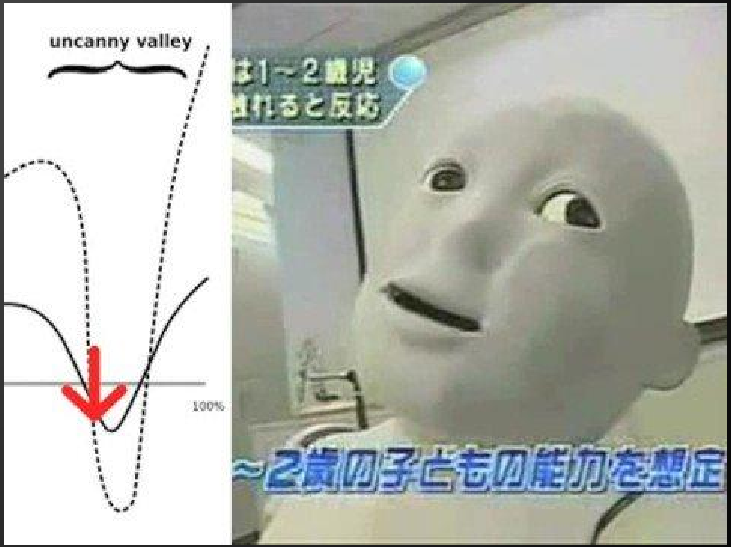
Tokyo University
Teaching robot



Uncanny valley

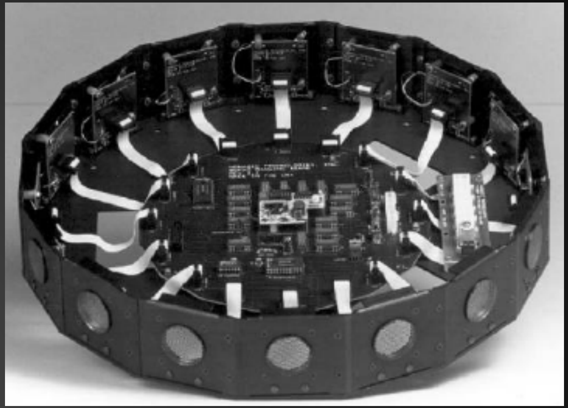
- human-like robots might seem “creepy”
- it is called the uncanny valley



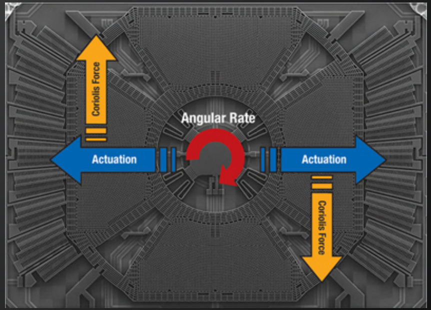


Sensors

- active
  - emits signal to the environment
  - RADAR
  - SONAR
- passive
  - only receives signal already present in the environment
  - IR sensor for human body detection
  - accelerometer, gyroscope



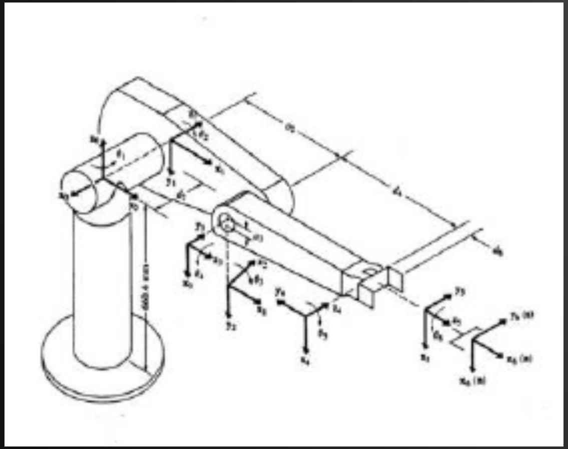
SONAR ring

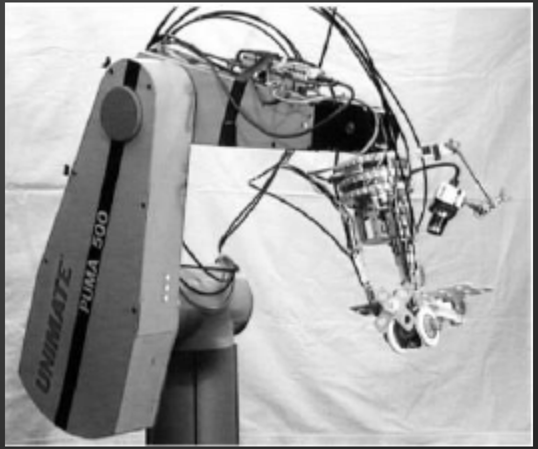


MEMS gyroscope

Manipulators

- manipulators are composed of links and joints
- flexibility is measured in degrees of freedom (DOF)





Puma by Unimation, branch of Westinghouse (6 DOF)

Utah/MIT robot hand

Manipulators

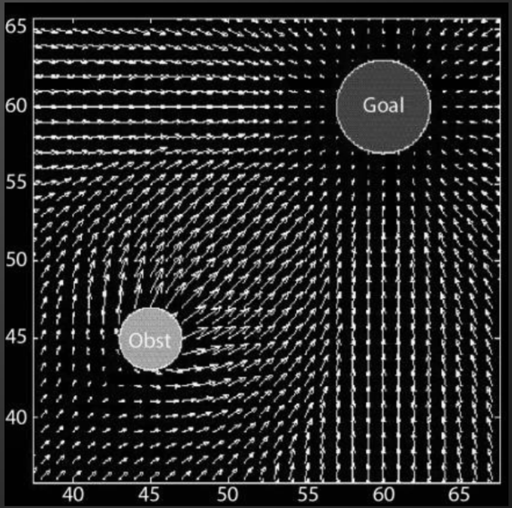
- arm links can be seen as kinematic chains
- forward kinematic
  - known robot configuration → arm position
  - Denavit-Hartenberg (1955)
- backward kinematic
  - arm position → robot configuration (ambiguous)

Part II: Mobility

Potential fields

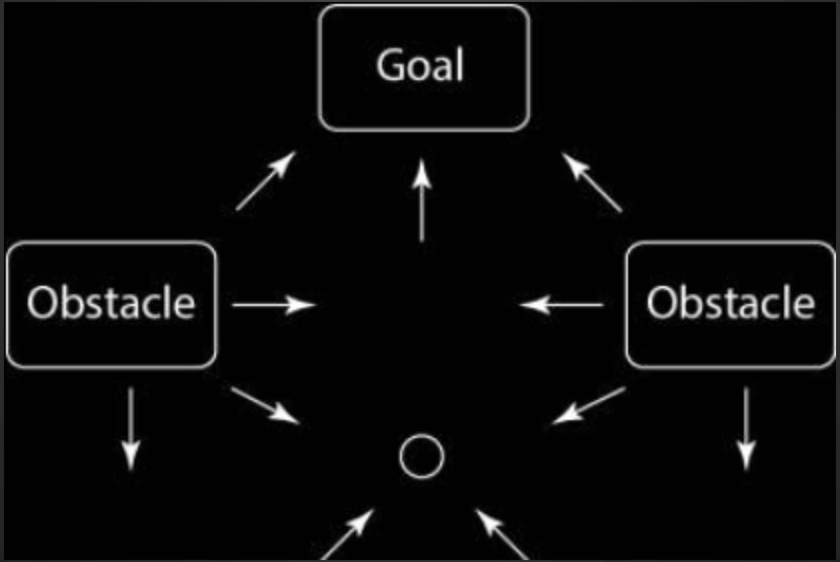
- one of the simplest methods to reach a goal position
- goal can also represent desired position of manipulator arm

$$(\Delta x, \Delta y) = \nabla P(x,y) = \left(\frac{\partial P}{\partial x}, \frac{\partial P}{\partial y} \right)$$



Potential fields

- obstacles can emit repulsive force

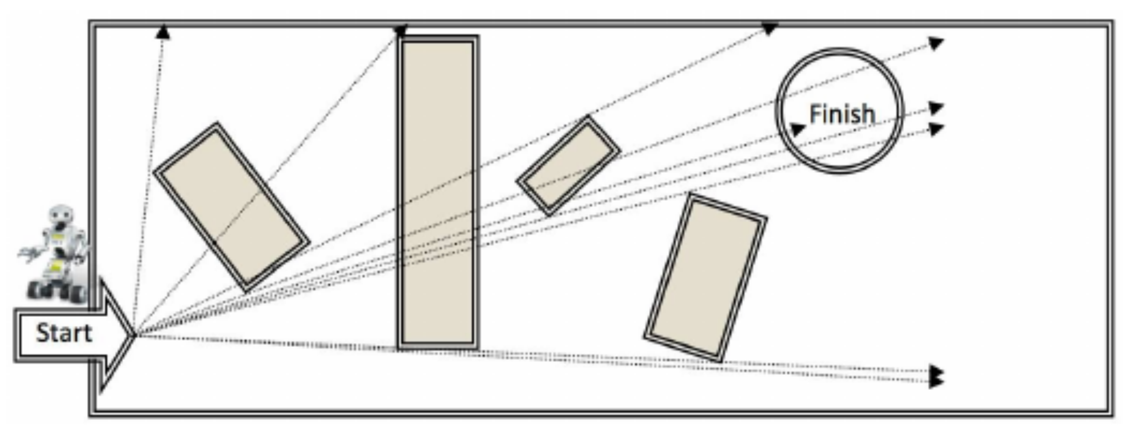


Roadmaps

- a robot might need a map of its environment
- roadmap is usually a represented as a graph structure with nodes as places and edges as roads
- path is a set of connected roads
  - for path finding, the most common algorithm is A* and its variations
- vector map
  - graphs of nodes and edges to denote vertices of polygons
- raster map
  - the map is sampled to cells which might be occupied or free

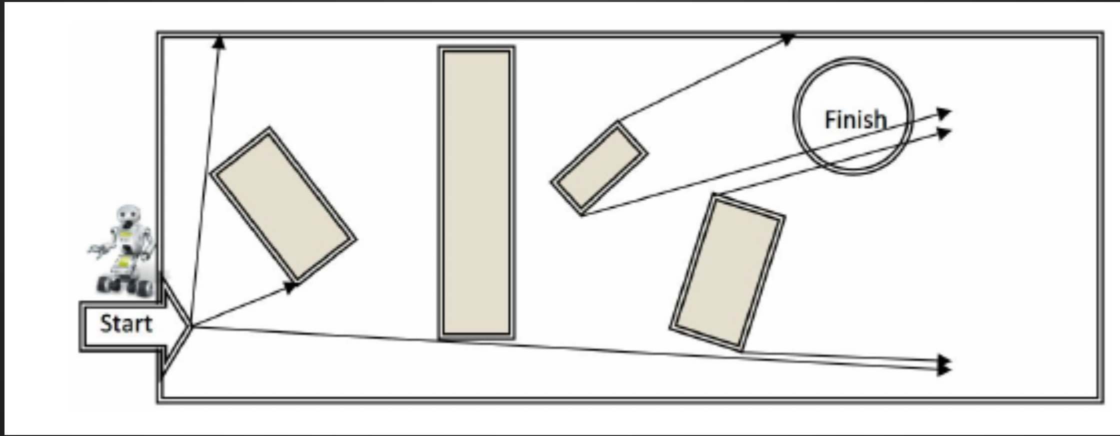
Geometry-based Roadmaps

1. radial sweep from the start point



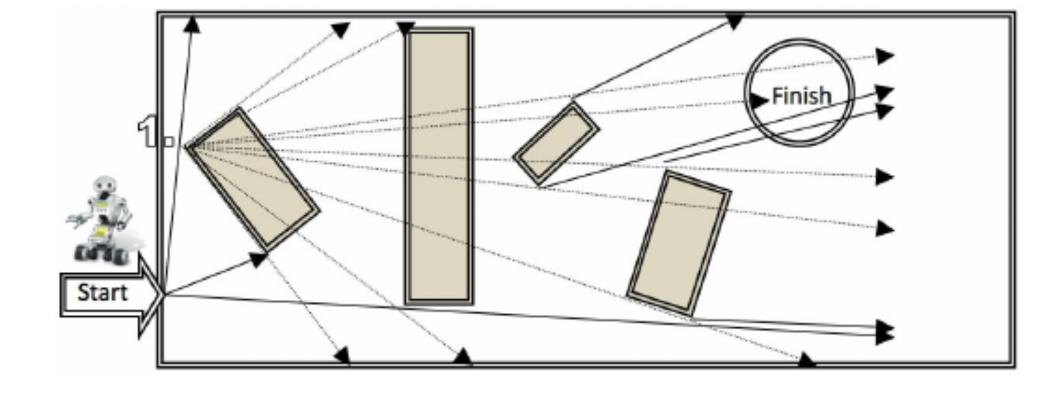
Geometry-based Roadmaps

2. remove invalid paths by eliminating segment colliding with an obstacle



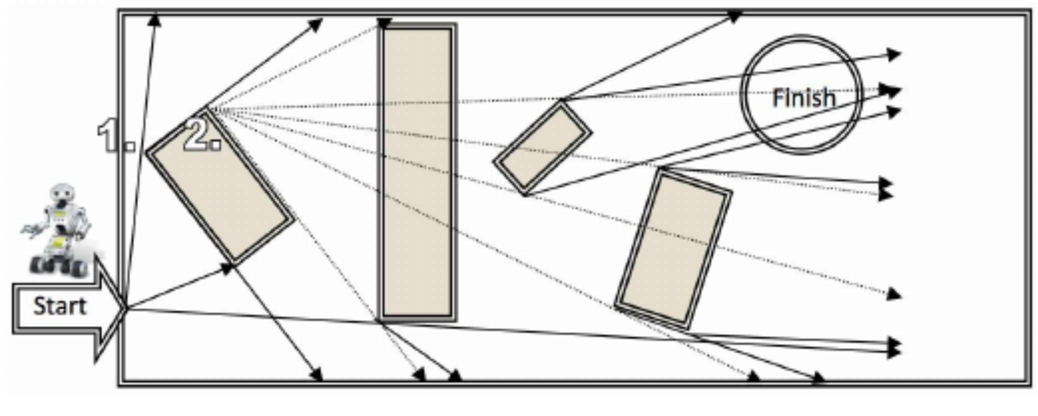
Geometry-based Roadmaps

3. repeat using each obstacle vertex as new starting point



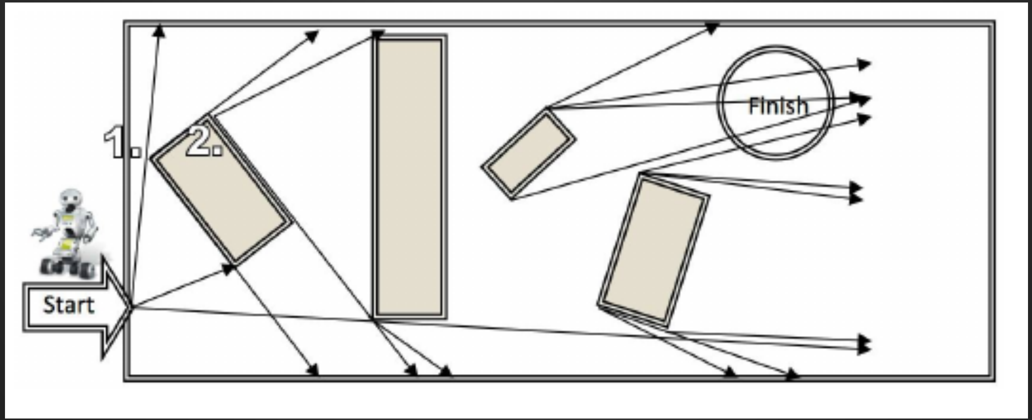
Geometry-based Roadmaps

3. repeat using each obstacle vertex as new starting point



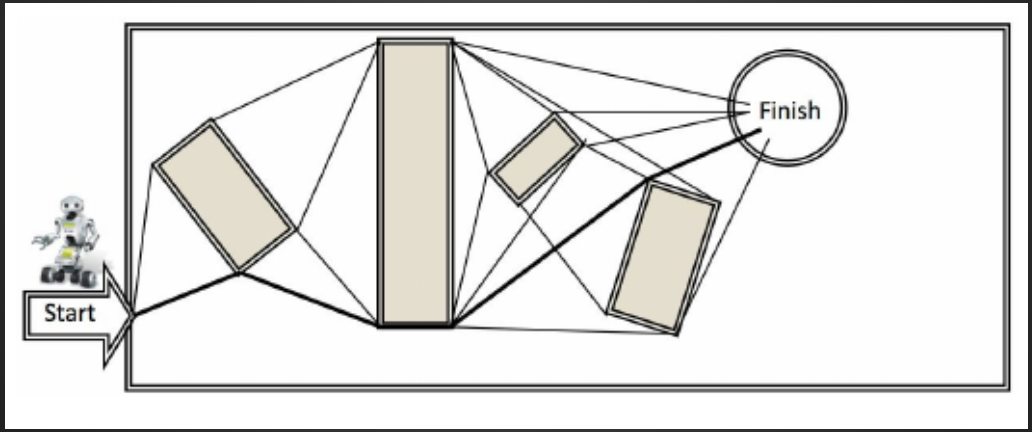
Geometry-based Roadmaps

3. repeat using each obstacle vertex as new starting point



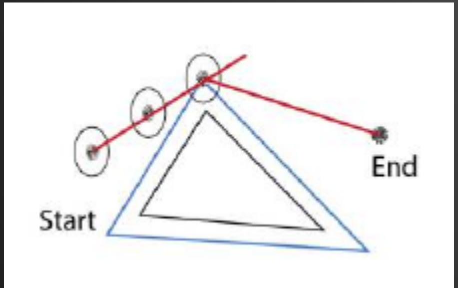
Geometry-based Roadmaps

4. convert to visibility graph of obstacle vertices

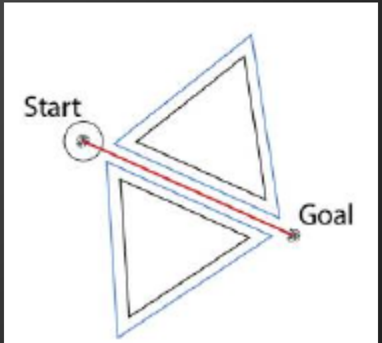


Geometry-based Roadmaps

- to avoid collisions, the obstacles might be dilated
- dilatation can, however, cause problems with narrow passages



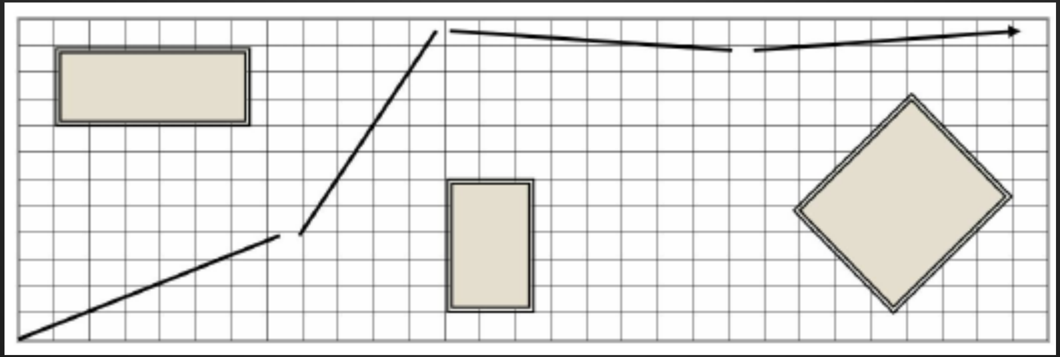
obstacle dilatation



narrow passage

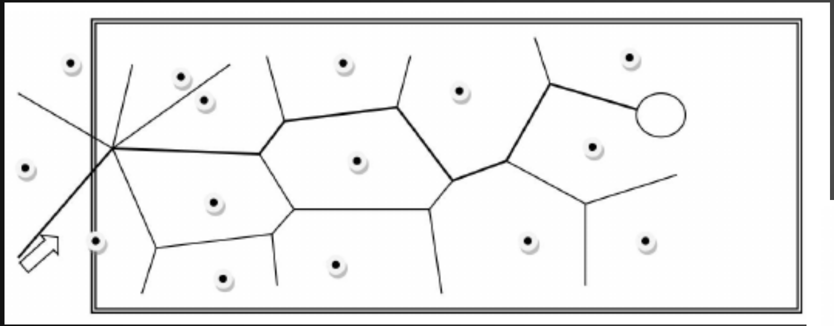
Grids

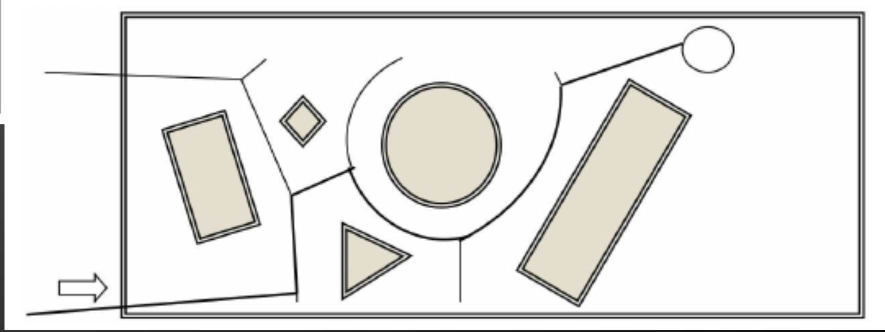
- basic occupancy map
- resolution of the grid is an issue
  - large grids have a lower resolution and may result in blocking paths
  - higher resolution is computationally expensive



Voronoi Roadmaps (Grid-based Approach)

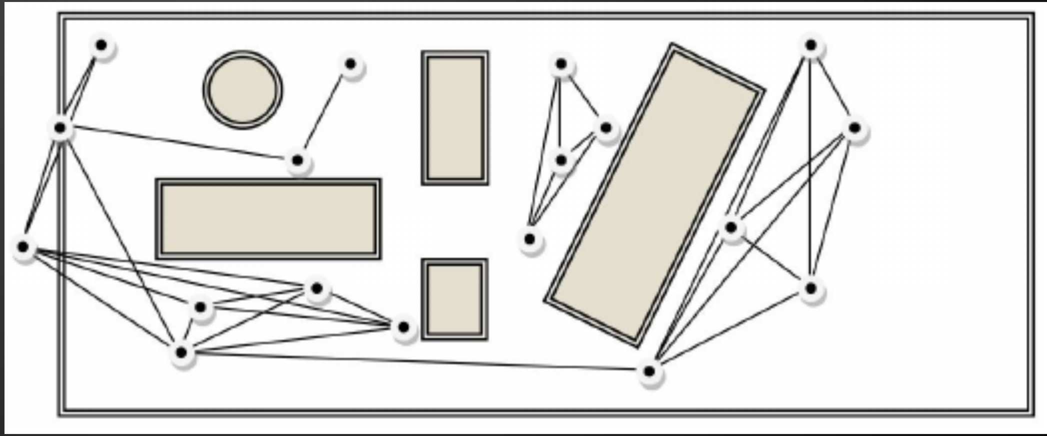
- offers maximum clearance between obstacles





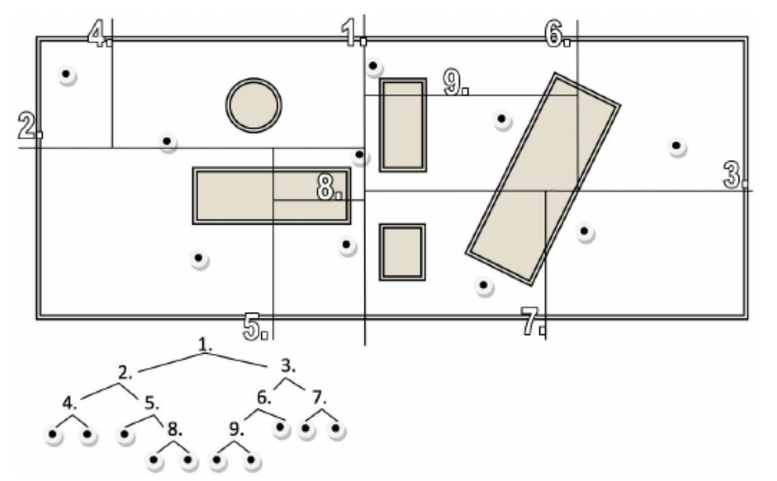
Probabilistic Roadmaps

- created by randomly selecting free points and interconnecting them
- not necessarily lead to a solution as the graph might not be connected



Probabilistic Roadmaps - KD Trees

- probably the most popular probabilistic method
- constructed by alternatively subdividing cells with vertical and horizontal lines
- the tree is used to identify probable neighbors
- the goal is to have one point per cell



Rapidly Exploring Random Tree (RRT)

- can be built by constructing rooted graph at the start location and randomly going toward the goal

1. **Let V** contain the start vertex and let **E** be empty
2. **Repeat**
   a. **Let q** be a random valid robot configuration (i.e., a random point)
   b. **Let v** be the node of **V** that is closest to **q**
   c. **Let p** be the point along the ray from **v** to **q** that is at distance s from **v**
   d. **IF** (**vp** is a valid edge) **THEN** add new node **p** to **V** with parent **v**
3. **Until V** has **n** vertices //

Parameters of the algorithm are:

- Number of nodes represented by n
- Edge Length (step size) of exploration represented by s

Roadmaps: Conclusions

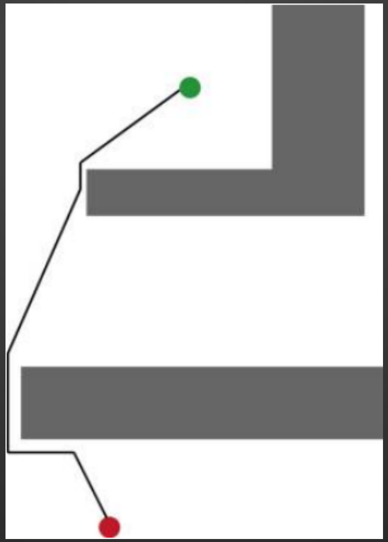
- roadmaps have been one of the most extensively explored area of robotics
- with reliable positioning, the need for outdoor map building disappears
- there exist a few commercial projects (such as at Google) that offer indoor maps for public use
- in the absence of available maps, robot has to build its own maps

Reactive Navigation

- study of planning and controlling course and position of the robot toward a desired location, where knowledge of objects in the environment is only known after the movement begins
- navigation is a set of reactive strategies
- often called bug algorithms

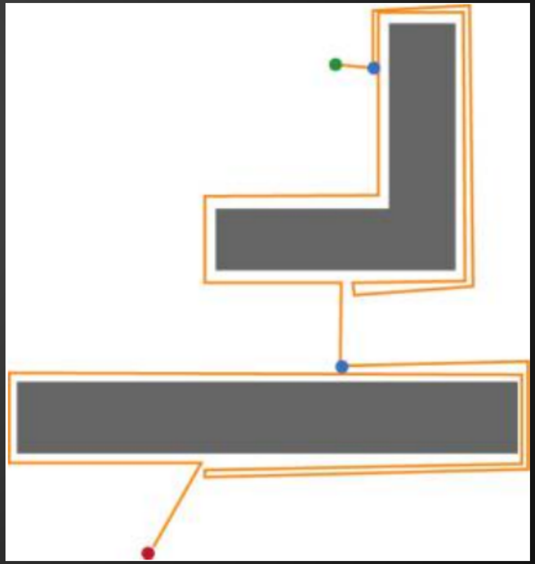
Bug 0 Strategy

1. Head toward the goal
2. Follow obstacles until you can head toward the goal again
3. Continue



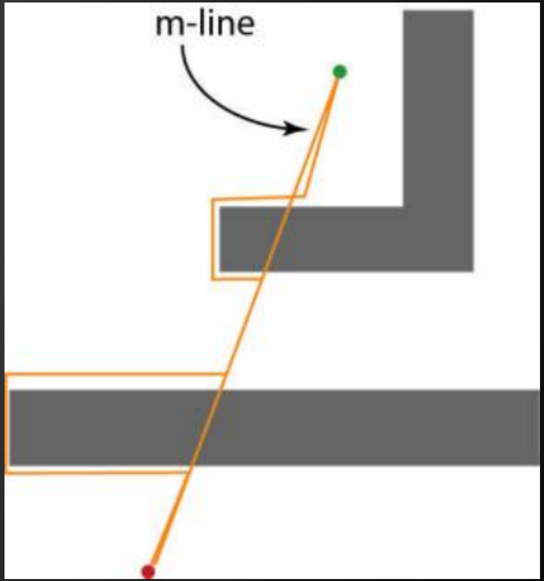
Bug 1 Strategy

1. go around an obstacle in order to find the point closest to the goal
2. travel back to the closest point
3. resume moving toward the goal



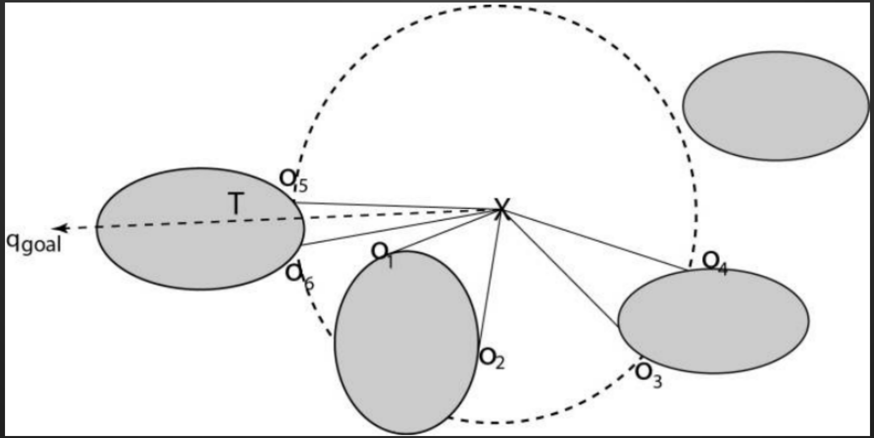
Bug 2 Strategy

1. move toward the goal along the m-line
2. if an obstacle is encountered move along its perimeter until the m-line is reached



Tangent Bug Strategy

- considers a robot with 360° proximity sensor with a limited range
- robot chooses the discontinuity point minimizing the travel distance to the goal



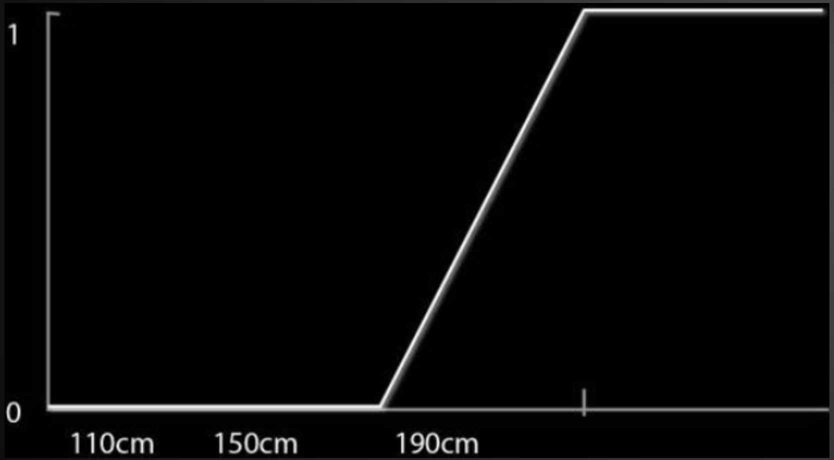
Multi-Robot Mapping

- Ants algorithm
  - at the start, all cells are marked with a zero
  - at each steps, agent picks the least visited cell to move into
  - flexible and fault tolerant
- Multiple depth-first search
  - each agent builds its own DFS tree and stores its own ID in the cells
  - agents stay in their own trees, unless they exhaust unexplored cells

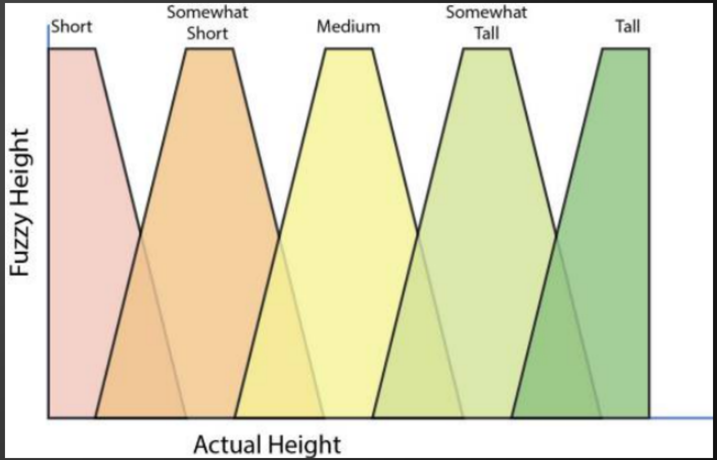
IF the current cell is unexplored, **THEN** mark it as explored
Annotate the cell with your ID
Annotate the cell with the direction of the previous cell (parent cell)
END IF
IF there are unexplored cell around, then go to one of them randomly
ELSE IF the current cell is marked with your ID, **THEN** mark it as visited
Go to the parent cell
ELSE go to one of the explored cells randomly
END IF
END IF

Fuzzy Control

- captures imprecision in human natural language



example of a fuzzy membership for the concept of “tall”



Another fuzzy membership functions: people consider overlapping height average concepts rather than a single function