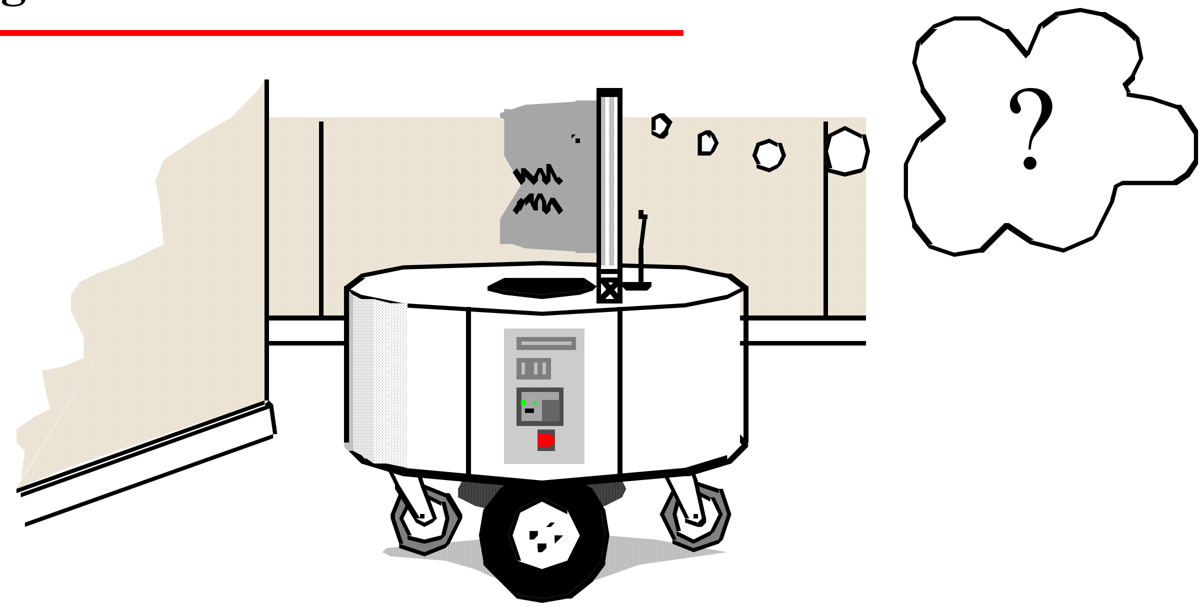
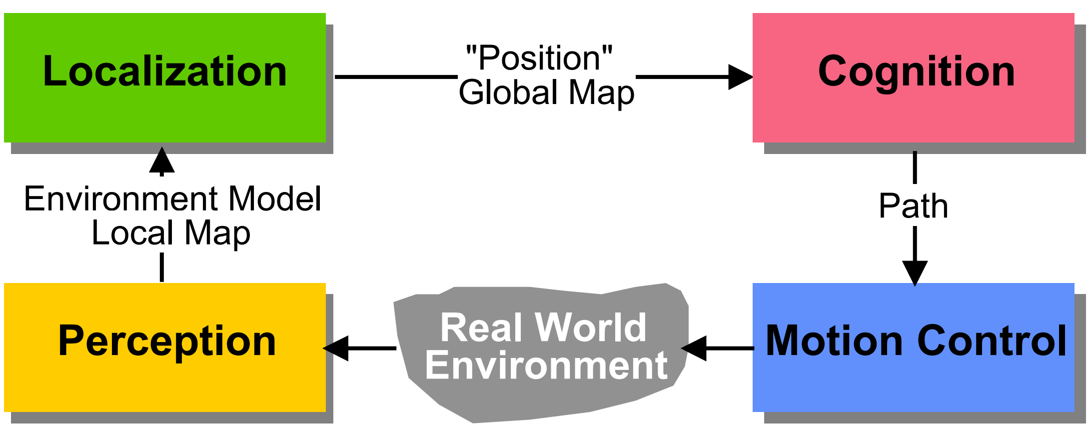
Planning and Navigation

Where am I going? How do I get there?





Competencies for Navigation I

- Cognition / Reasoning :
  - *is the ability to decide* **what actions are required** *to achieve a* **certain goal** *in a* **given situation (belief state)**.
  - *decisions ranging from* **what path to take** *to what* **information on the environment to use**.
- Today's industrial robots can operate without any cognition (reasoning) because their environment is static and very structured.
- In mobile robotics, cognition and reasoning is primarily of geometric nature, such as picking safe path or determining where to go next.
  - *already been largely explored in literature for cases in which complete information about the current situation and the environment exists (e.g. traveling salesman problem).*

Competencies for Navigation II

- However, in mobile robotics the knowledge of about the environment and situation is usually only partially known and is uncertain.
  - *makes the task much more difficult*
  - *requires multiple tasks running in parallel, some for planning (global), some to guarantee "survival of the robot".*
- Robot control can usually be decomposed in various behaviors or functions
  - *e.g. wall following, localization, path generation or obstacle avoidance.*
- In this chapter we are concerned with path planning and navigation, (and assume low level motion control and localization).
- We can generally distinguish between (*global*) path planning and (*local*) obstacle avoidance.

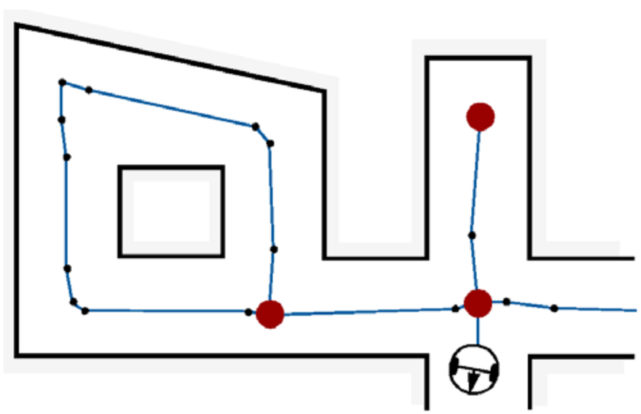
Global Path Planning

- Assumption: there exists a good enough map of the environment for navigation.
  - *Topological or metric or a mixture between both.*
- First step:
  - *Representation of the environment by a road-map (graph), cells or a potential field. The resulting discrete locations or cells allow then to use standard planning algorithms.*
- Examples:
  - *Visibility Graph*
  - *Voronoi Diagram*
  - *Cell Decomposition -> Connectivity Graph*
  - *Potential Field*

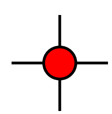
Path Planning Overview

1. Road Map, Graph construction

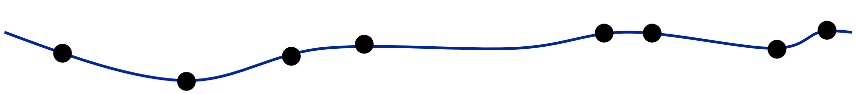
- *Identify a set of routes within the free space*



- Where to put the nodes?
- Topology-based:
  - *at distinctive locations*

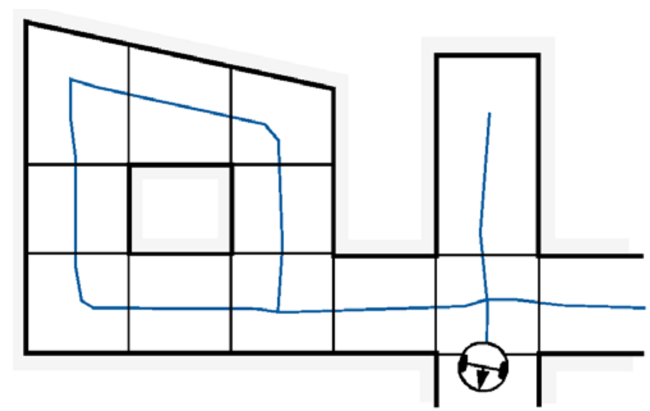


- Metric-based:
  - *where features disappear or get visible*



2. Cell decomposition

- *Discriminate between free and occupied cells*

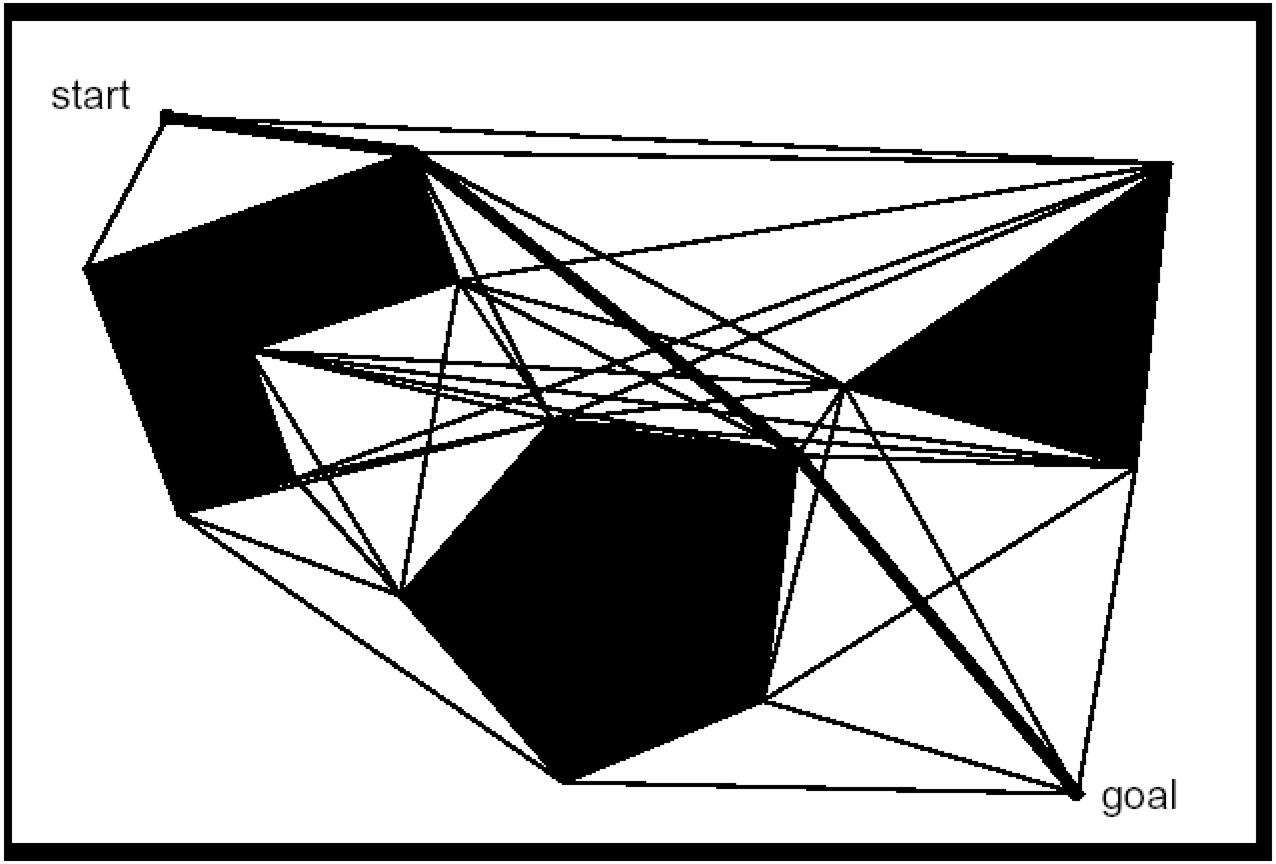


- Where to put the cell boundaries?
- Topology- and metric-based:
  - *where features disappear or get visible*

3. Potential Field

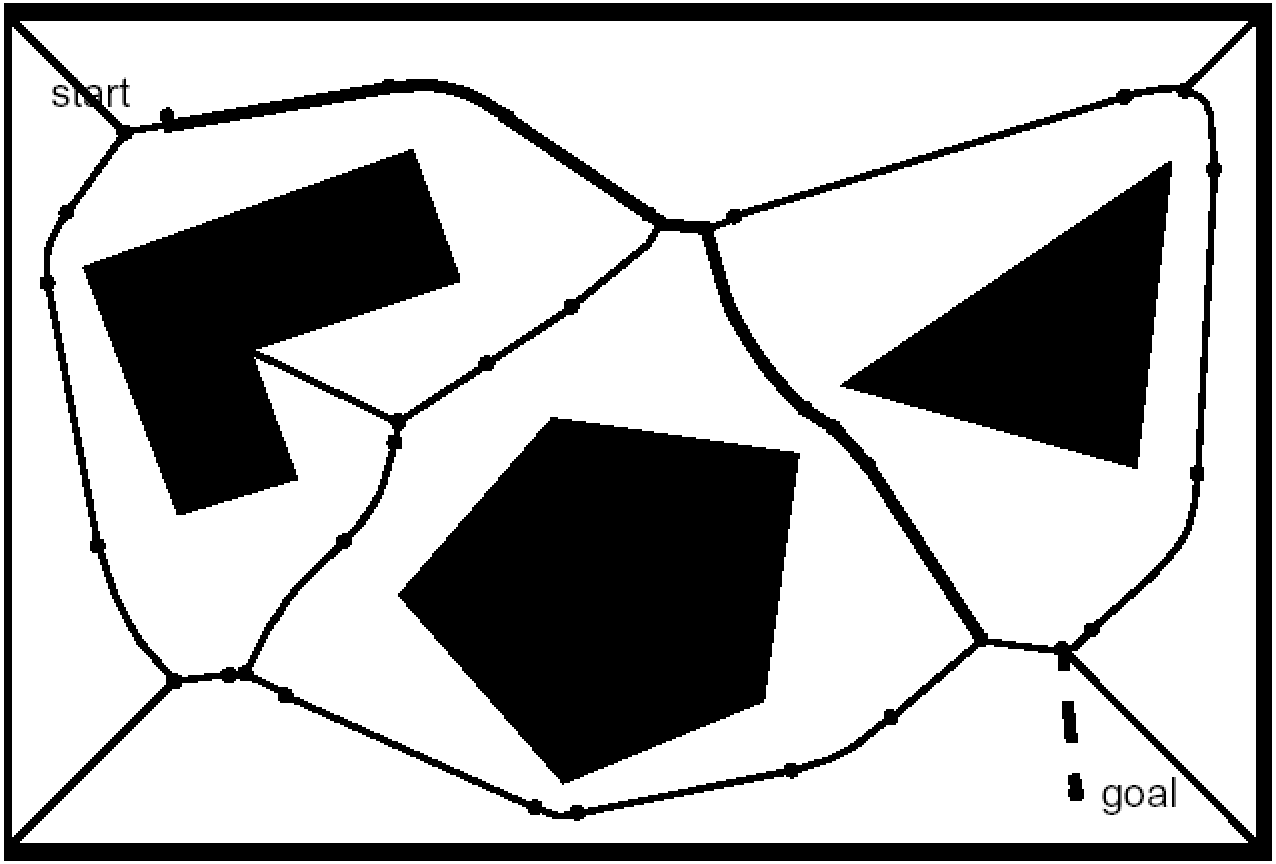
- *Imposing a mathematical function over the space*

Road-Map Path Planning: **Visibility Graph**



- Shortest path length
- Grow obstacles to avoid collisions

Road-Map Path Planning: **Voronoi Diagram**

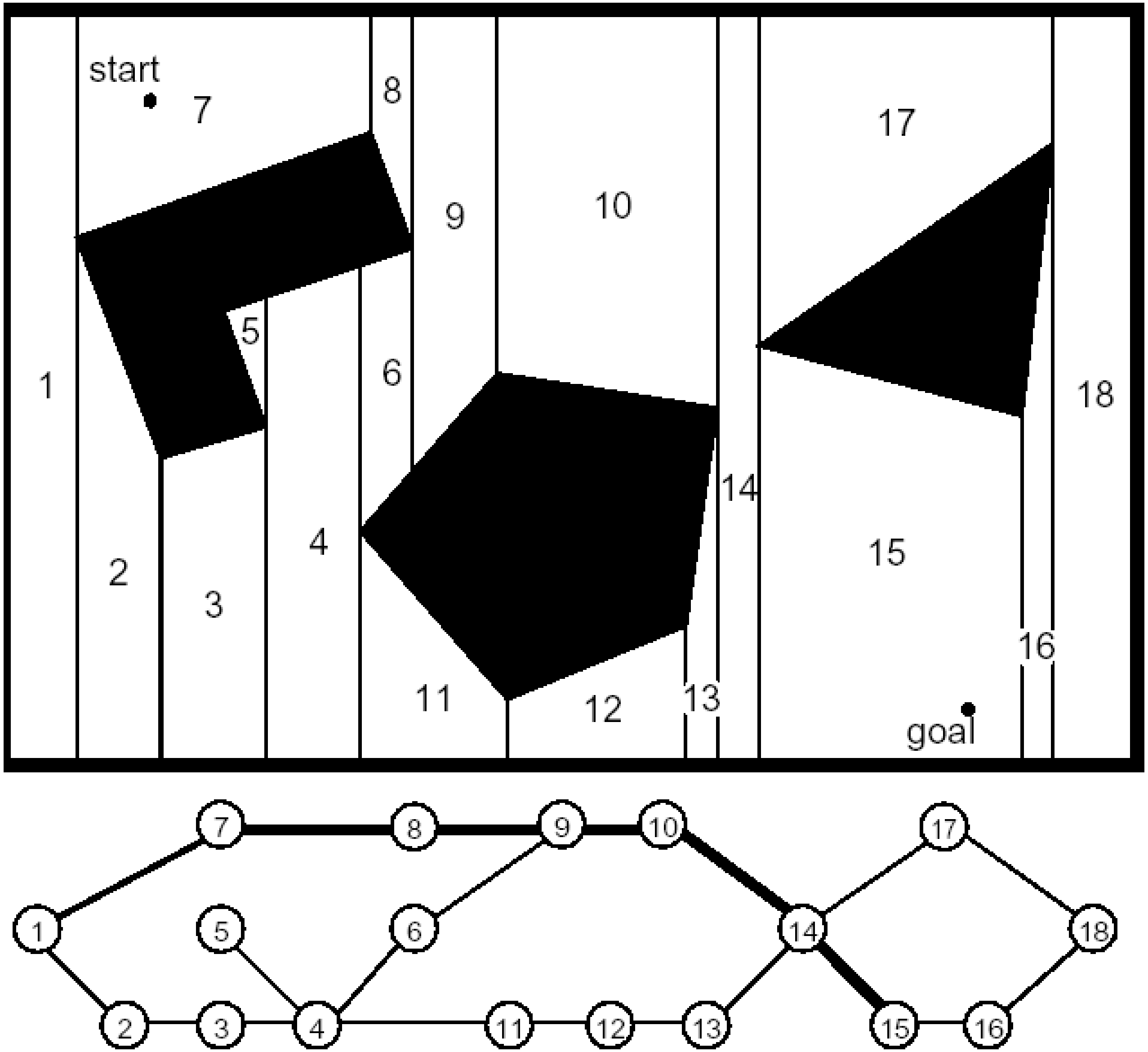


- Easy executable: Maximize the sensor readings
- Works also for map-building: Move on the Voronoi edges

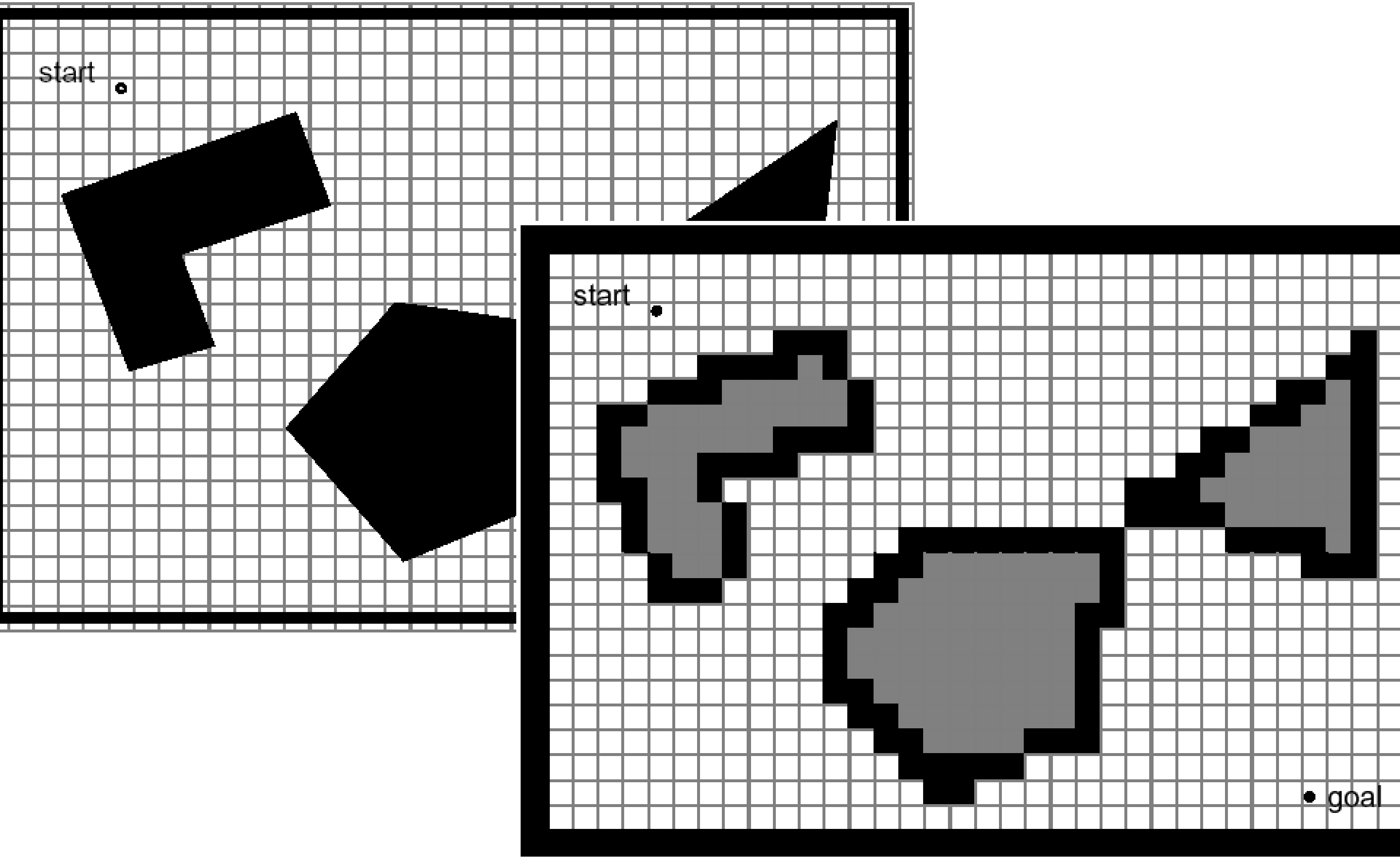
Road-Map Path Planning: **Cell Decomposition**

- Divide space into simple, connected regions called cells
- Determine which open cells are adjacent and construct a connectivity graph
- Find cells in which the initial and goal configuration (state) lie and search for a path in the connectivity graph to join them.
- From the sequence of cells found with an appropriate search algorithm, compute a path within each cell.
    - *e.g. passing through the midpoints of cell boundaries or by sequence of wall following movements.*

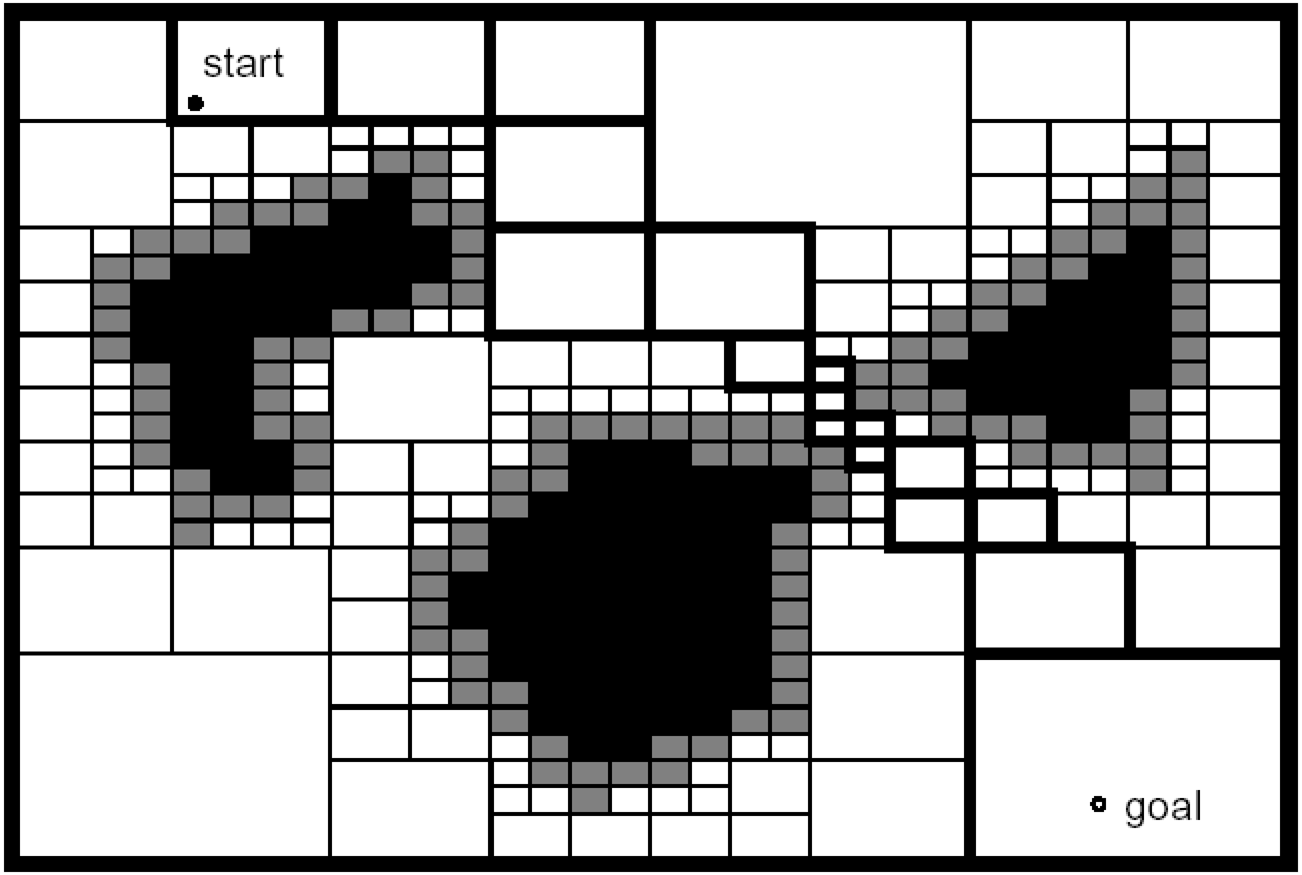
Road-Map Path Planning: **Exact Cell Decomposition**



Road-Map Path Planning: **Approximate Cell Decomposition**

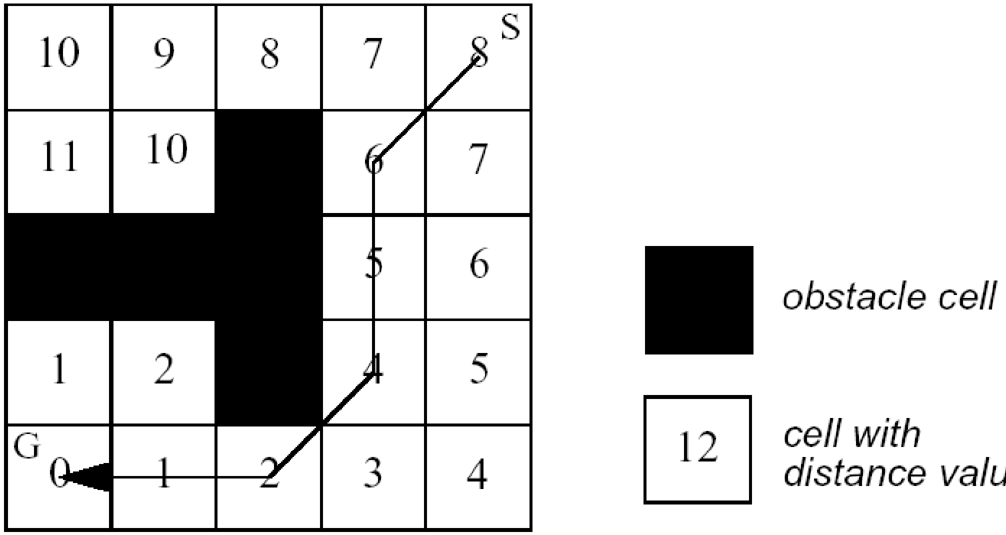


Road-Map Path Planning: **Adaptive Cell Decomposition**



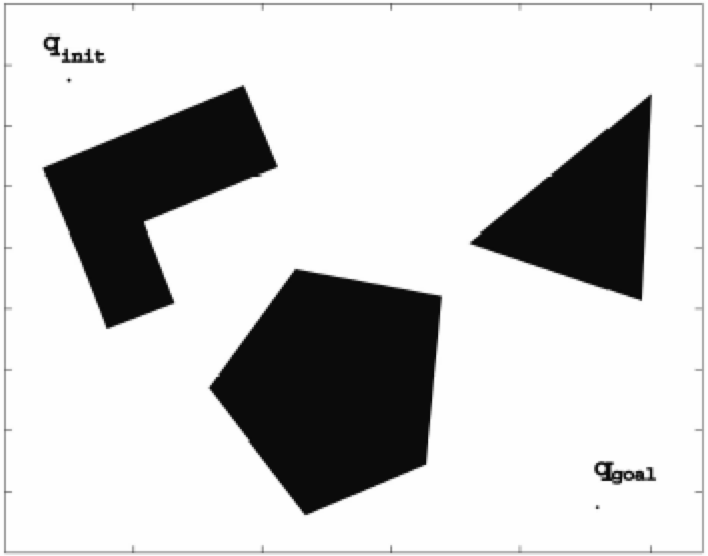
Road-Map Path Planning: **Path / Graph Search Strategies**

- Wavefront Expansion NF1 (see also later)

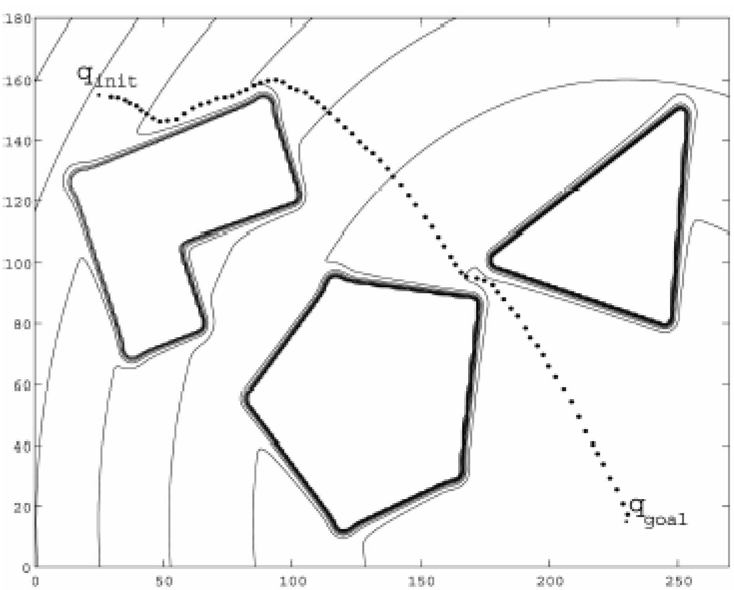


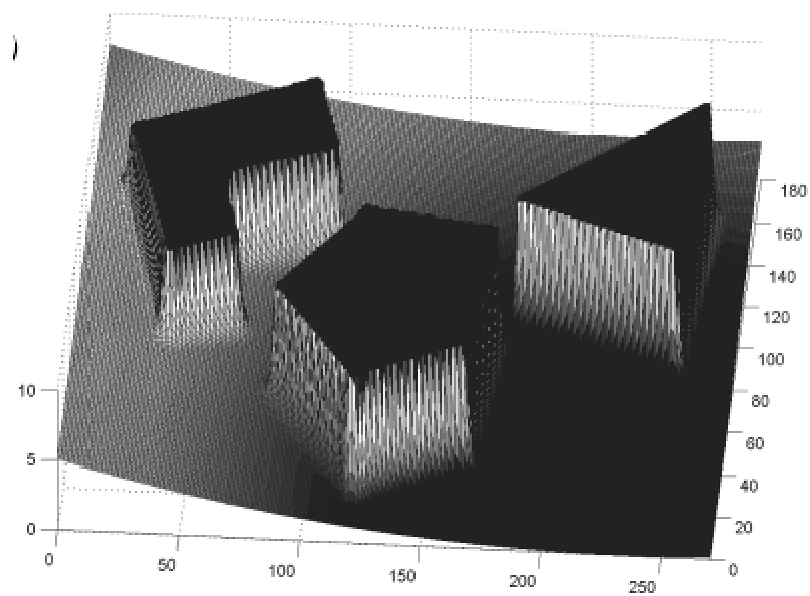
- Breadth-First Search
- Depth-First Search
- Greedy search and A*

Potential Field Path Planning



- Robot is treated as a *point under the influence* of an artificial potential field.
  - *Generated robot movement is similar to a ball rolling down the hill*
  - *Goal generates attractive force*
  - *Obstacle are repulsive forces*





Potential Field Path Planning: **Potential Field Generation**

- Generation of potential field function *U(q)*
  - *attracting (goal) and repulsing (obstacle) fields*
  - *summing up the fields*
  - *functions must be differentiable*
- Generate artificial force field *F(q)*

$$F(q) = -\nabla U(q) = -\nabla U_{att}(q) - \nabla U_{rep}(q) = \begin{bmatrix} \frac{\partial U}{\partial x} \\ \frac{\partial U}{\partial y} \end{bmatrix}$$

- Set robot speed (v_x, v_y) proportional to the force $F(q)$ generated by the field
  - *the force field drives the robot to the goal*
  - *if robot is assumed to be a point mass*

Potential Field Path Planning: **Attractive Potential Field**

- Parabolic function representing the Euclidean distance $\|q - q_{goal}\|$ to the goal

$$U_{att}(q) = \frac{1}{2}k_{att} \cdot \rho^2_{goal}(q)$$

- Attracting force converges linearly towards 0 (goal)

$$\begin{aligned} F_{att}(q) &= -\nabla U_{att}(q) \\ &= -k_{att} \cdot \rho_{goal}(q)\nabla\rho_{goal}(q) \\ &= -k_{att} \cdot (q - q_{goal}) \end{aligned}$$

Potential Field Path Planning: **Repulsing Potential Field**

- Should generate a barrier around all the obstacle
  - *strong if close to the obstacle*
  - *no influence if far from the obstacle*

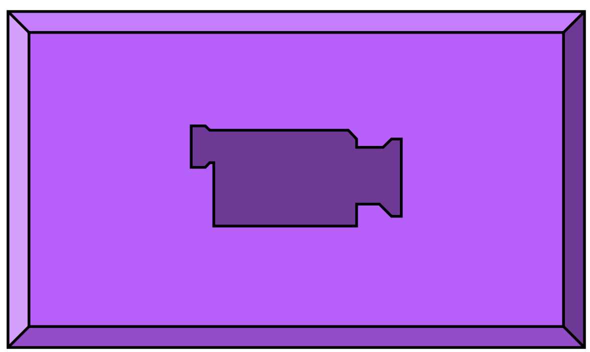
$$U_{rep}(q) = \begin{cases} \frac{1}{2}k_{rep}\left(\frac{1}{\rho(q)} - \frac{1}{\rho_0}\right)^2 & \text{if } \rho(q) \le \rho_0 \\ 0 & \text{if } \rho(q) \ge \rho_0 \end{cases}$$

  - $\rho(q)$ *: minimum distance to the object*
  - *Field is positive or zero and* tends to infinity *as q gets closer to the object*

$$F_{rep}(q) = -\nabla U_{rep}(q) = \begin{cases} k_{rep}\left(\frac{1}{\rho(q)} - \frac{1}{\rho_0}\right)\frac{1}{\rho^2(q)}\frac{q - q_{goal}}{\rho(q)} & \text{if } \rho(q) \le \rho_0 \\ 0 & \text{if } \rho(q) \ge \rho_0 \end{cases}$$

Potential Field Path Planning: **Sysquake Demo**

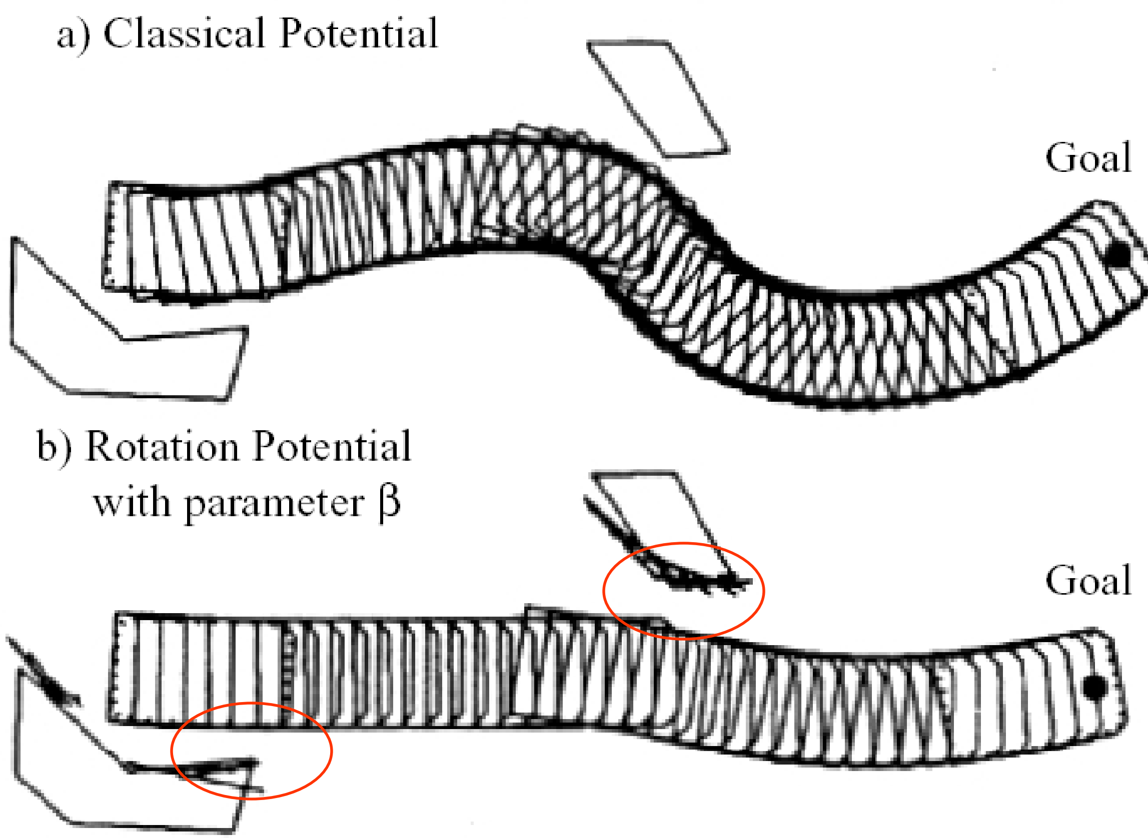
- Notes:
  - *Local minima problem exists*
  - *Problem becomes more complex if the robot is not considered as a point mass*
  - *If objects are convex there exists situations where several minimal distances exist → can result in oscillations*



Potential Field Path Planning: **Extended Potential Field Method**

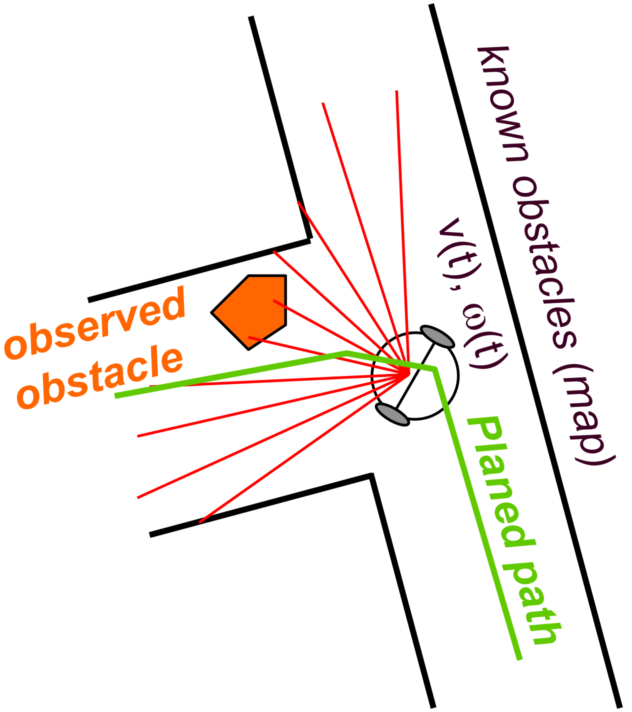
Khatib and Chati

- Additionally a *rotation potential field* and a *task potential field* in introduced
- Rotation potential field
  - ➢ *force is also a function of robot's orientation to the obstacle*
- Task potential field
  - ➢ *Filters out the obstacles that should not influence the robot's movements, i.e. only the obstacles in the sector Z in front of the robot are considered*

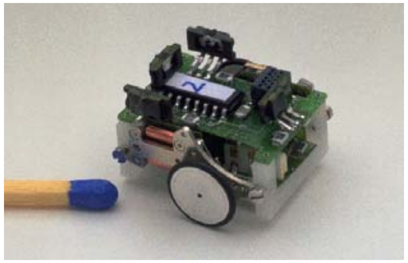


Obstacle Avoidance (Local Path Planning)

- The goal of the obstacle avoidance algorithms is to avoid collisions with obstacles
- It is usually based on *local map*
- Often implemented as a more or less *independent task*
- However, efficient obstacle avoidance should be optimal with respect to
  - *the overall goal*
  - *the actual speed and kinematics of the robot*
  - *the on board sensors*
  - *the actual and future risk of collision*

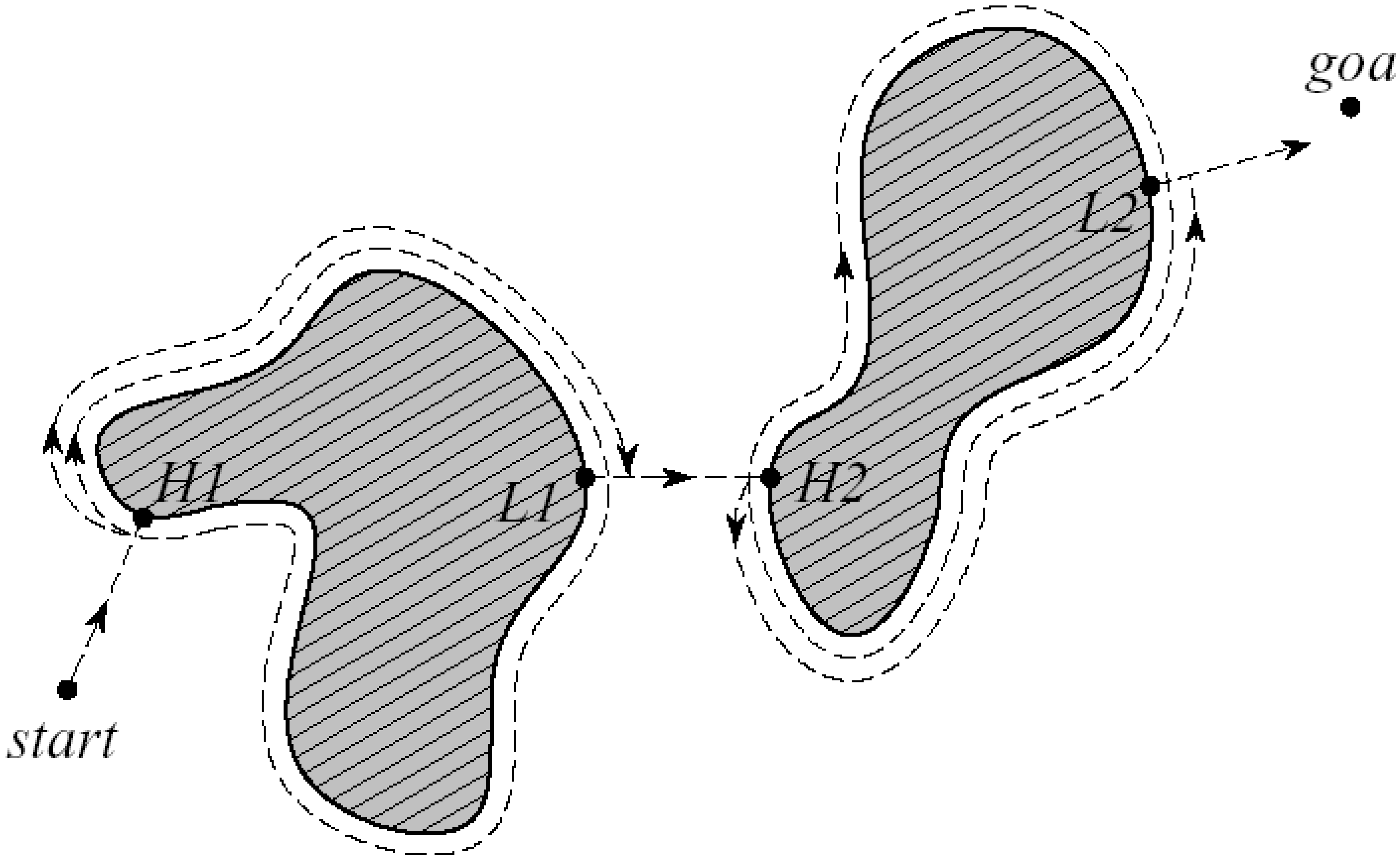


- Example: Alice



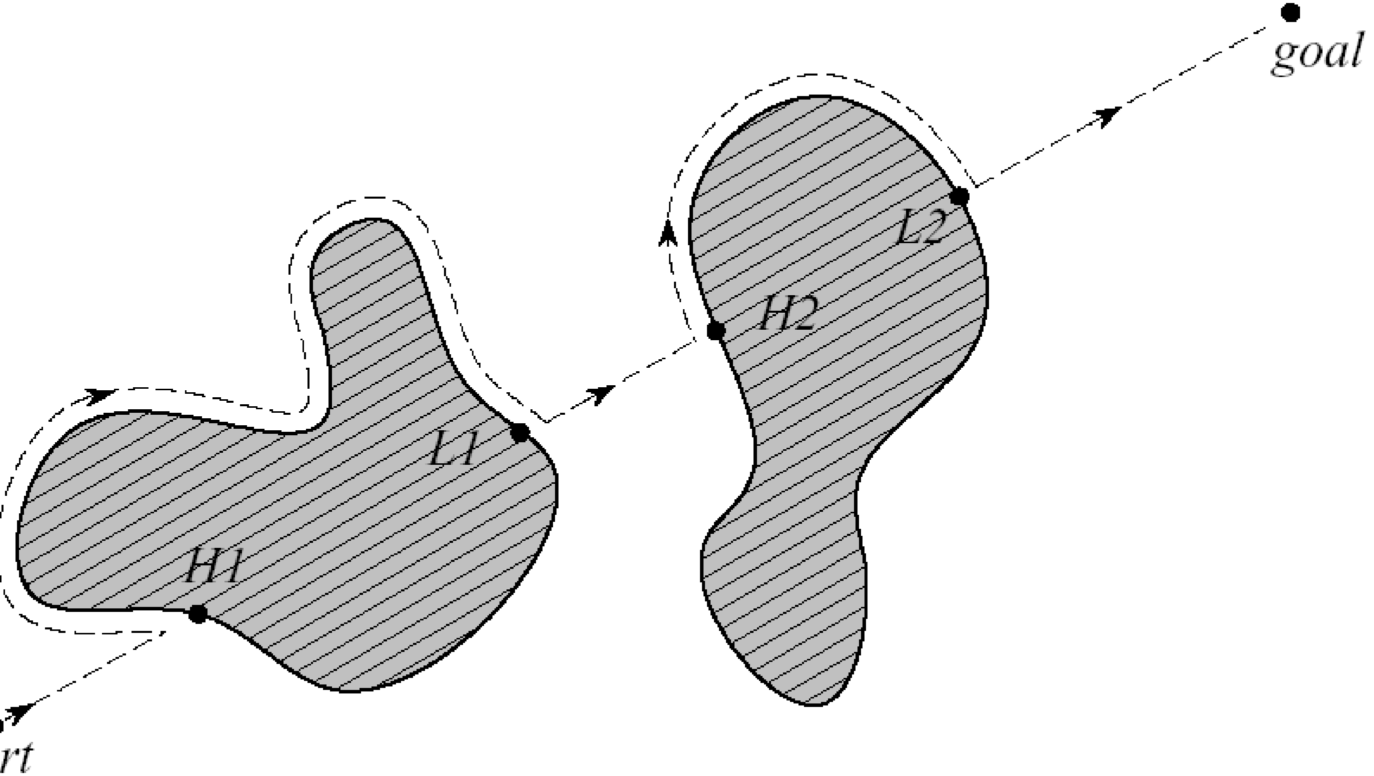
Obstacle Avoidance: **Bug1**

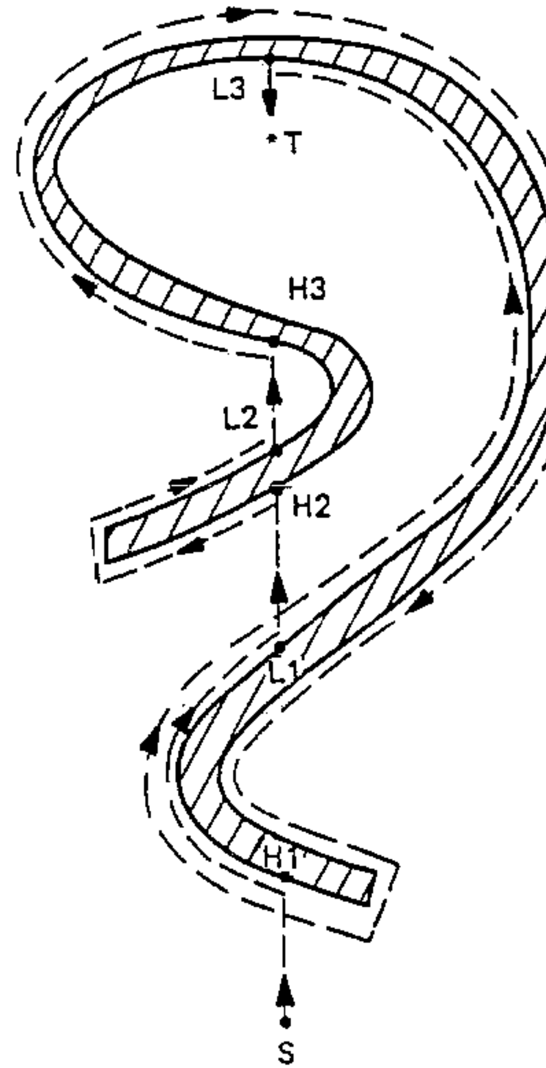
- Following along the obstacle to avoid it
- Each encountered obstacle is once fully circled before it is left at the point closest to the goal



Obstacle Avoidance: **Bug2**

- *Following the obstacle always on the left or right side*
- *Leaving the obstacle if the direct connection between start and goal is crossed*



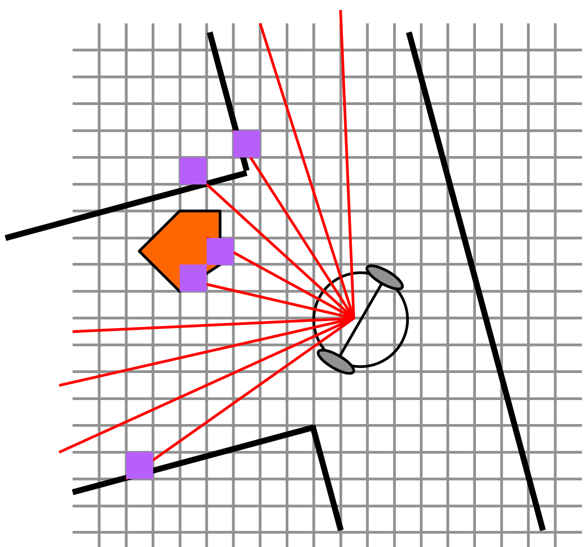


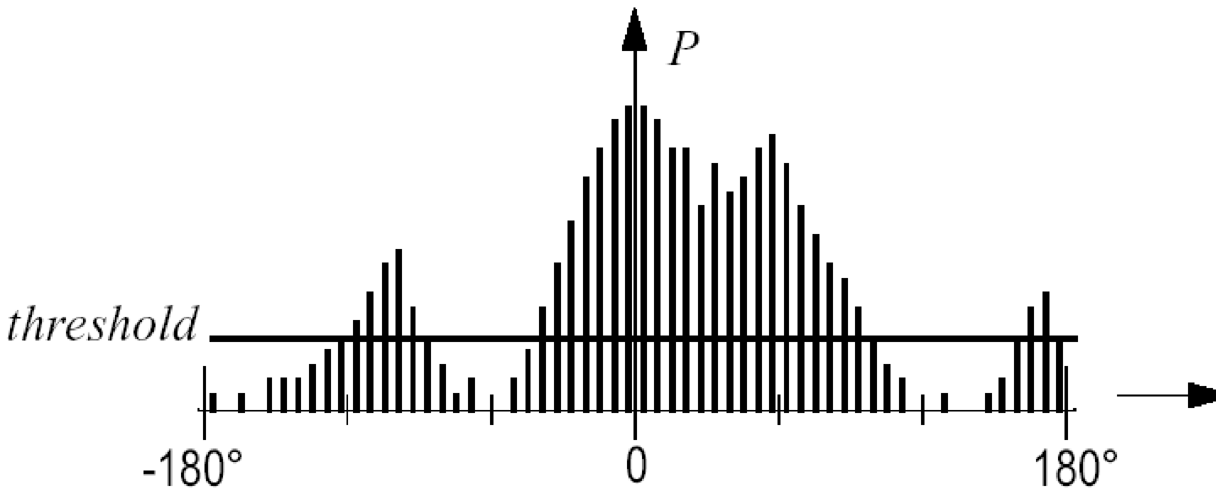
Obstacle Avoidance: **Vector Field Histogram (VFH)**

Borenstein et al.

- Environment represented in a grid (2 DOF)
  - *cell values equivalent to the probability that there is an obstacle*
- Reduction in different steps to a 1 DOF histogram
  - *calculation of steering direction*
  - *all openings for the robot to pass are found*
  - *the one with lowest cost function G is selected*

$$G = a \cdot \text{target\_direction} + b \cdot \text{wheel\_orientation} + c \cdot \text{previous\_direction}$$

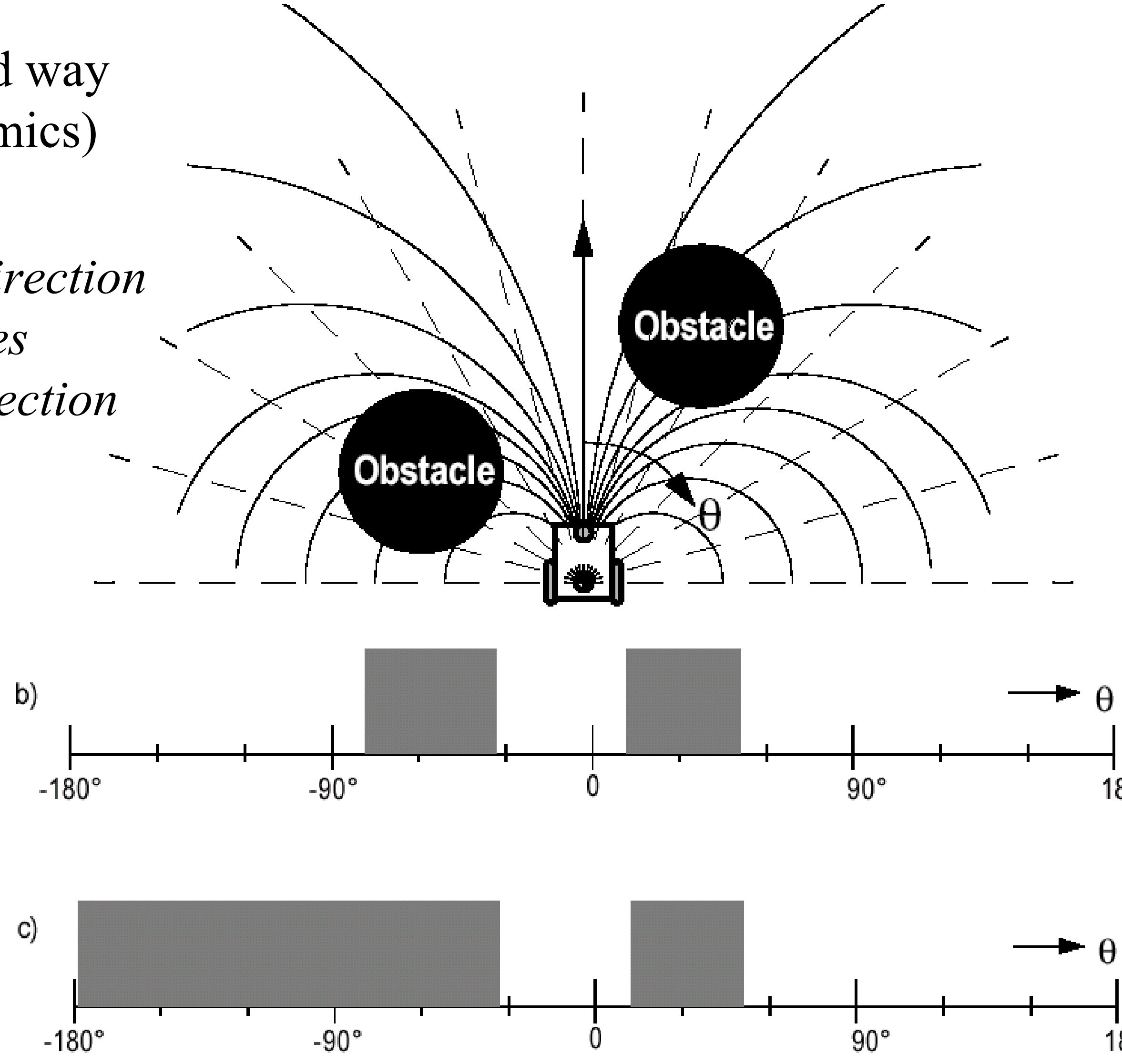




Obstacle Avoidance: **Vector Field Histogram + (VFH+)**

Borenstein et al.

- Accounts also in a very simplified way for the moving trajectories (dynamics)
  - *robot moving on arcs*
  - *obstacles blocking a given direction also blocks all the trajectories (arcs) going through this direction*



Obstacle Avoidance: **Video VFH**

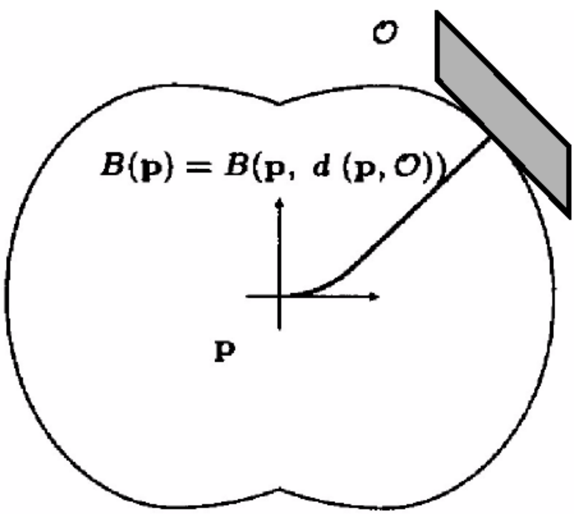
Borenstein et al.

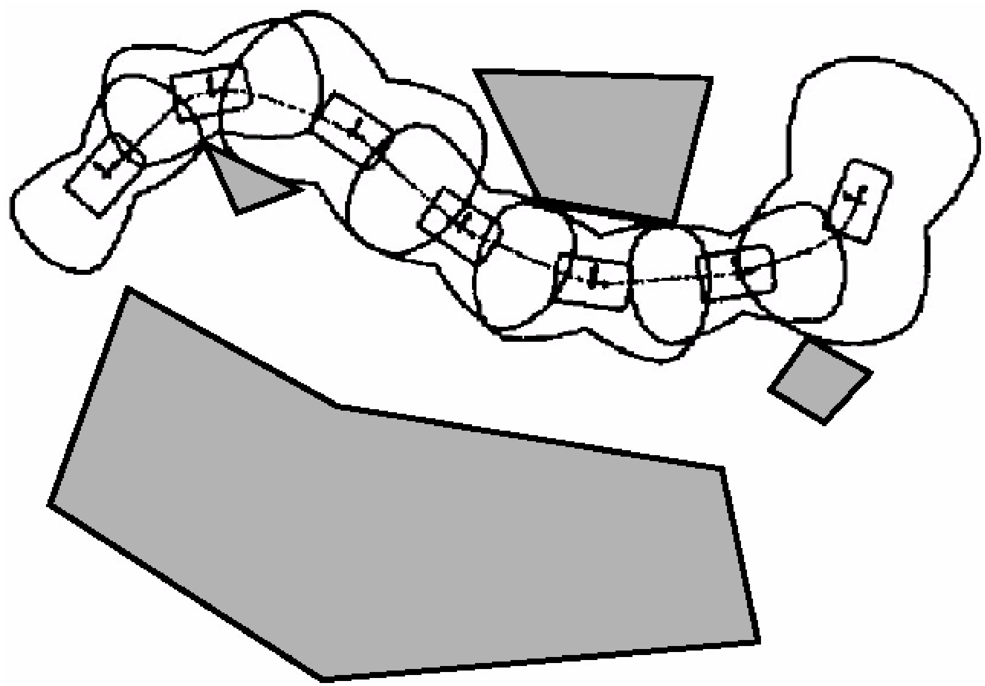
- Notes:
  - *Limitation if narrow areas (e.g. doors) have to be passed*
  - *Local minimum might not be avoided*
  - *Reaching of the goal can not be guaranteed*
  - *Dynamics of the robot not really considered*

Obstacle Avoidance: **The Bubble Band Concept**

Khatib and Chatila

- Bubble = Maximum free space which can be reached without any risk of collision
  - ➢ *generated using the distance to the object and a simplified model of the robot*
  - ➢ *bubbles are used to form a band of bubbles which connects the start point with the goal point*

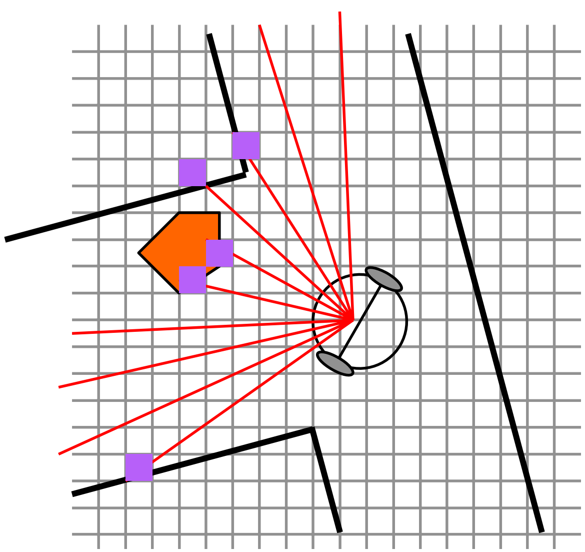


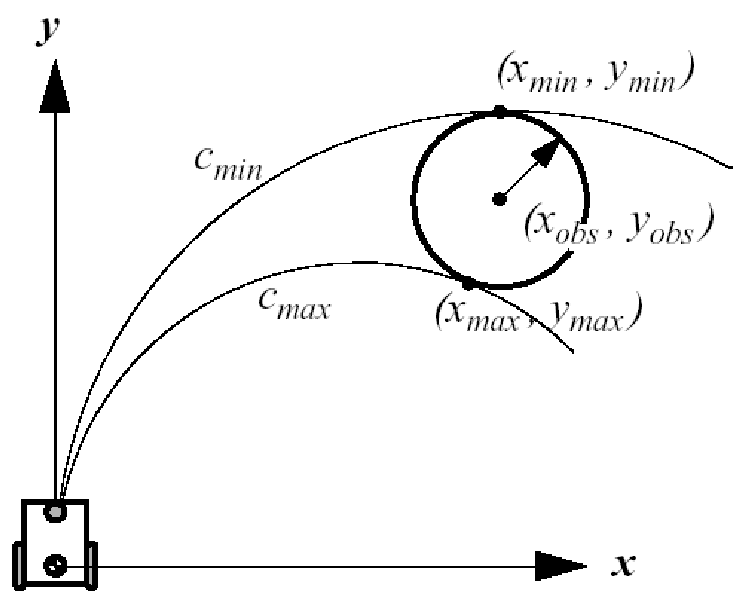


Obstacle Avoidance: Basic Curvature Velocity Methods (CVM)

Simmons et al.

- Adding *physical constraints* from the robot and the environment on the *velocity space* (*v*, ω) of the robot
  - *Assumption that robot is traveling on arcs (c= ω / v)*
  - *Acceleration constraints:*
  - *Obstacle constraints: Obstacles are transformed in velocity space*
  - *Objective function to select the optimal speed*





Obstacle Avoidance: Lane Curvature Velocity Methods (CVM)

Simmons et al.

- Improvement of basic CVM
  - *Not only arcs are considered*
  - *lanes are calculated trading off lane length and width to the closest obstacles*
  - *Lane with best properties is chosen using an objective function*

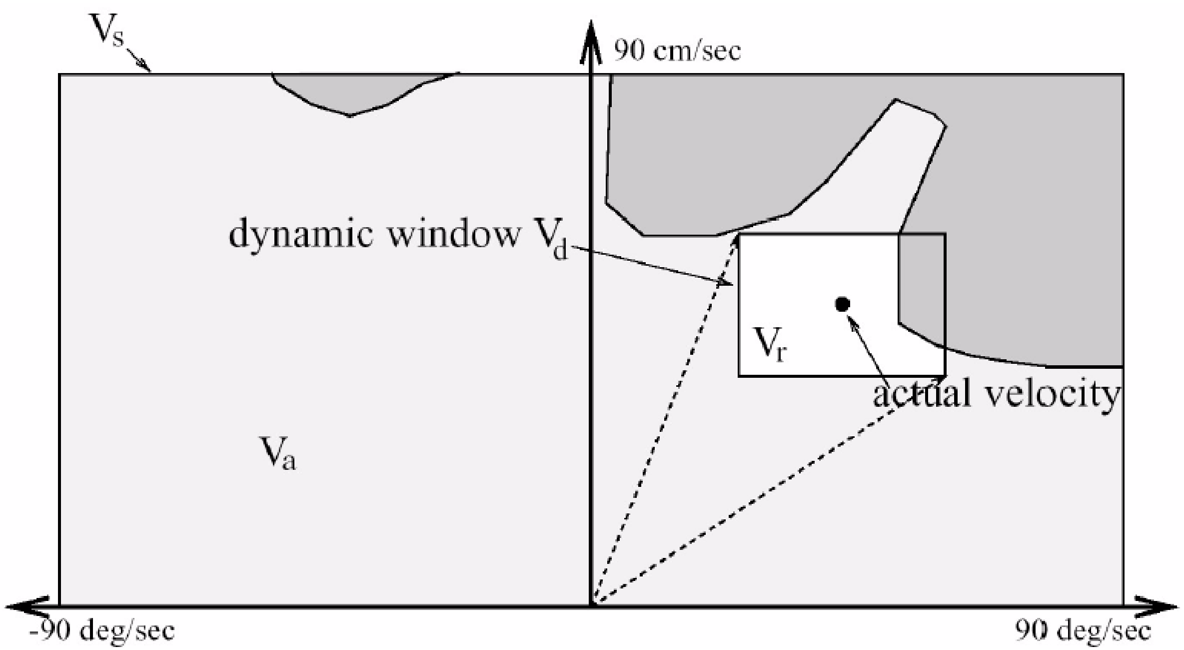
- Note:
  - *Better performance to pass narrow areas (e.g. doors)*
  - *Problem with local minima persists*

Obstacle Avoidance: **Dynamic Window Approach**

Fox and Burgard, Brock and Khati

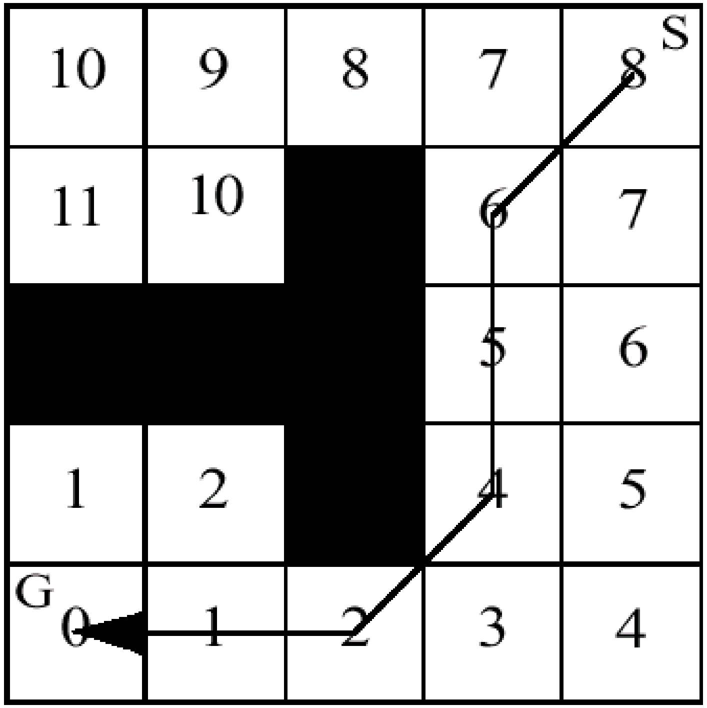
- The kinematics of the robot is considered by searching a well chosen velocity space
  - *velocity space -> some sort of configuration space*
  - *robot is assumed to move on arcs*
  - *ensures that the robot comes to stop before hitting an obstacle*
  - *objective function is chosen to select the optimal velocity*

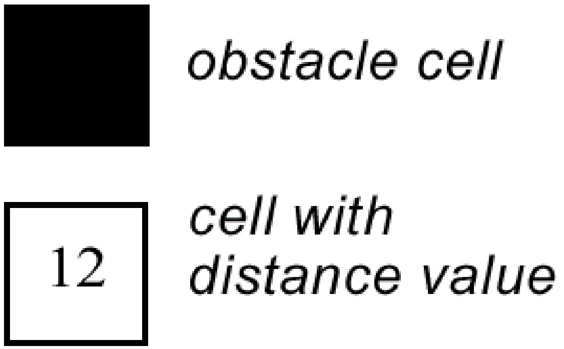
$$O = a \cdot heading(v, \omega) + b \cdot velocity(v, \omega) + c \cdot dist(v, \omega)$$



Obstacle Avoidance: Global **Dynamic Window Approach**

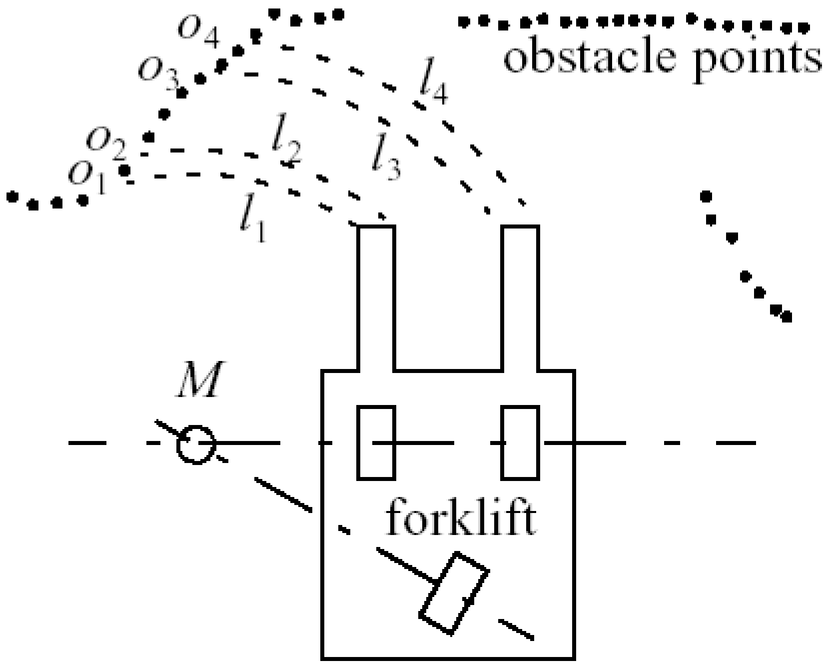
- Global approach:
  - *This is done by adding a minima-free function named NF1 (wave-propagation) to the objective function* O *presented above.*
  - *Occupancy grid is updated from range measurements*





Obstacle Avoidance: **The *Schlegel* Approach**

- Some sort of a variation of the dynamic window approch
  - *takes into account the shape of the robot*
  - *Cartesian grid and motion of circular arcs*
  - *NF1 planner*
  - *real time performance achieved by use of precalculated table*

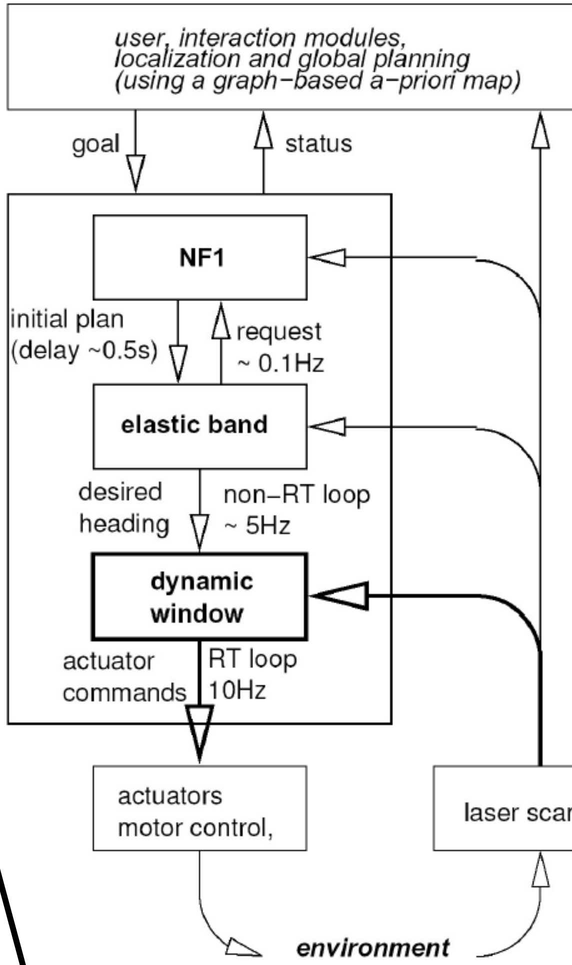


Obstacle Avoidance: **The EPFL-ASL approach**

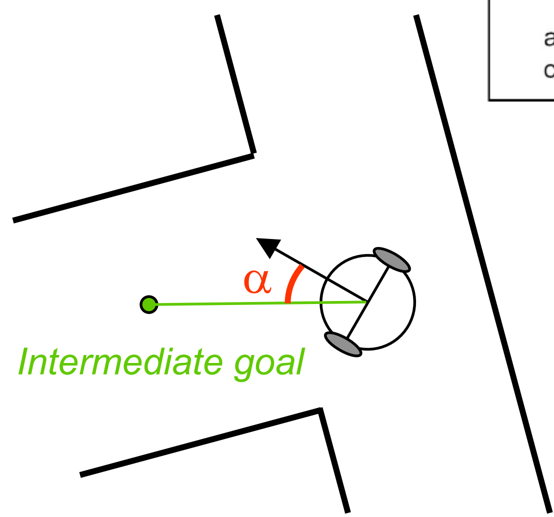
- Dynamic window approach with global path planing
  - *Global path generated in advance*
  - *Path adapted if obstacles are encountered*
  - *dynamic window considering also the shape of the robot*
  - *real-time because only max speed is calculated*
- Selection (Objective) Function:

$$Max(\, a \cdot speed + b \cdot dist + c \cdot goal\_heading \,)$$

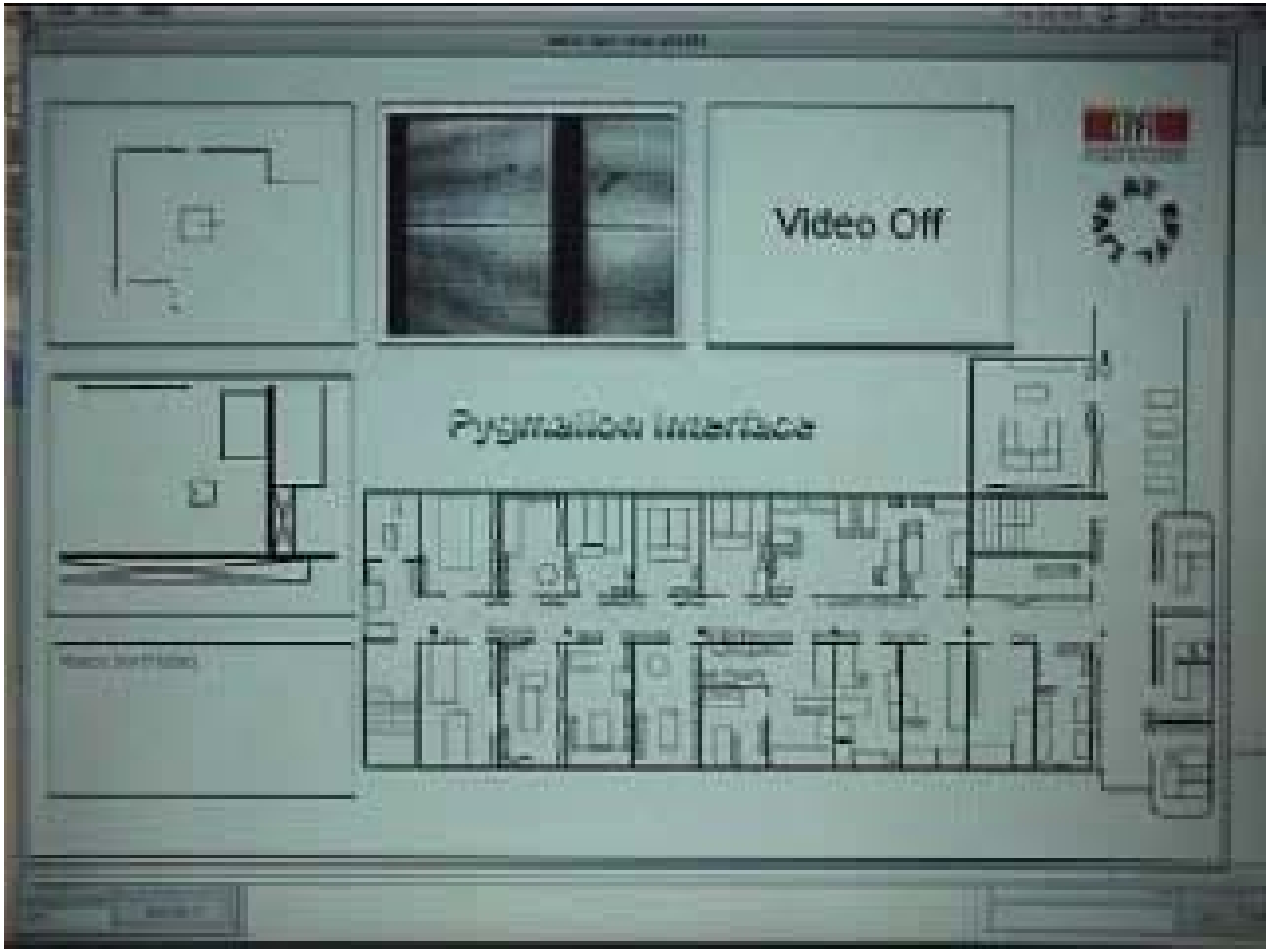
  - $speed = v / v_{max}$
  - $dist = L / L_{max}$
  - $goal\_heading = 1 - (\alpha - \omega T) / \pi$



- Matlab-Demo
  - *start Matlab*
  - *cd demoJan (or cd E:\demo\demoJan)*
  - *demoX*



Obstacle Avoidance: **The EPFL-ASL approach**

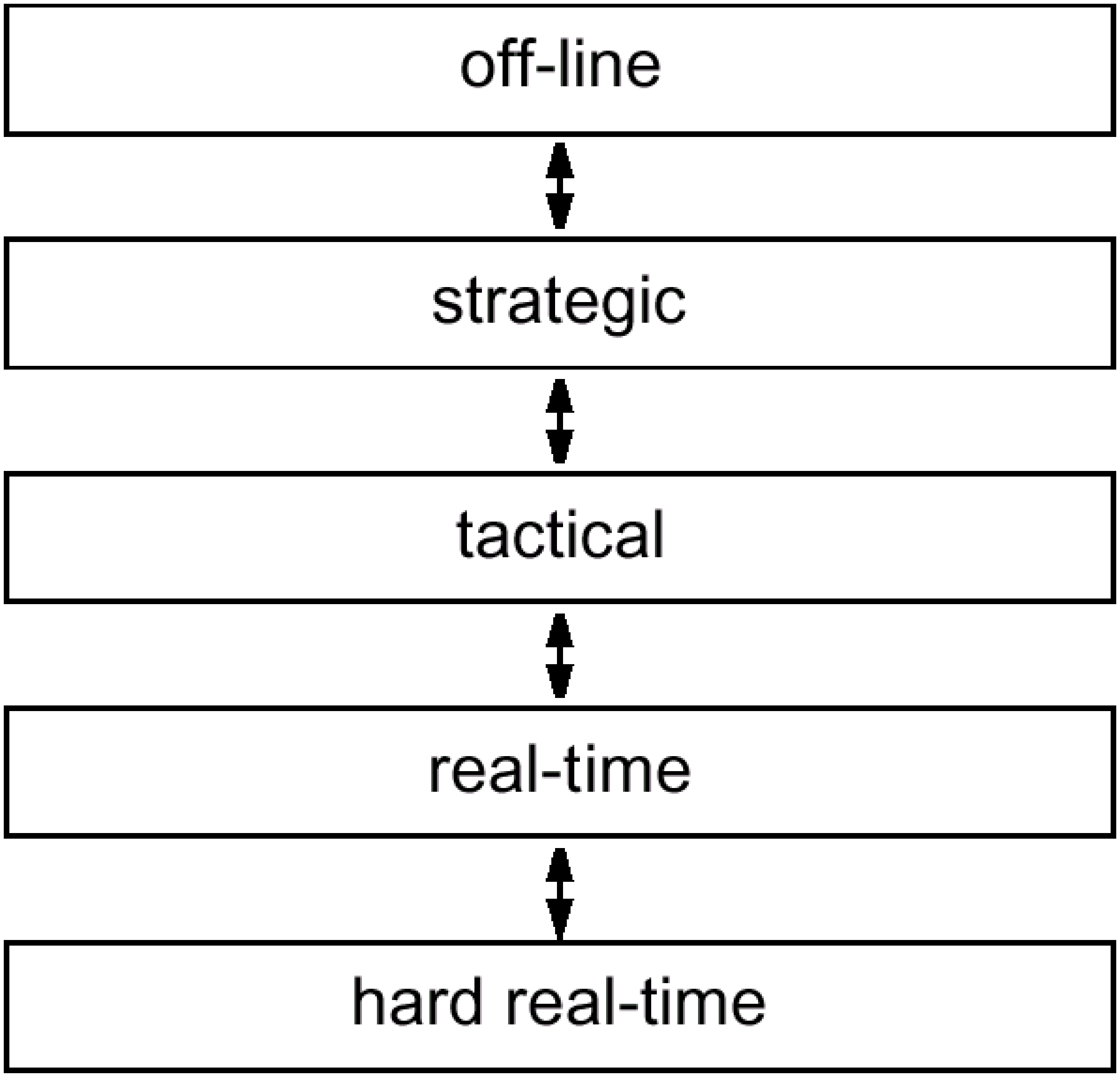


Obstacle Avoidance: **Other approaches**

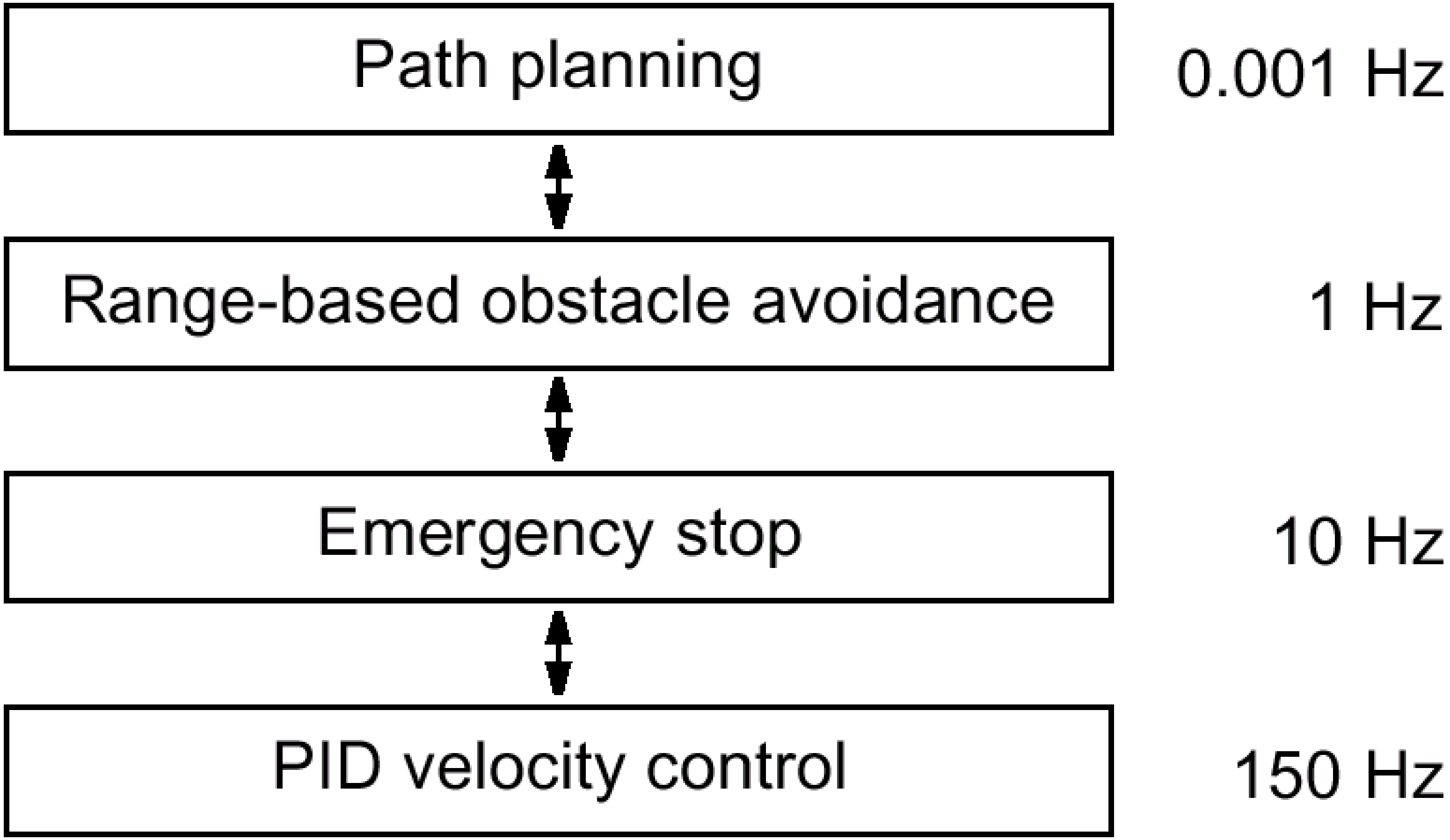
- Behavior based
  - *difficult to introduce a precise task*
  - *reachability of goal not provable*

- Fuzzy, Neuro-Fuzzy
  - *learning required*
  - *difficult to generalize*

Generic temporal decomposition

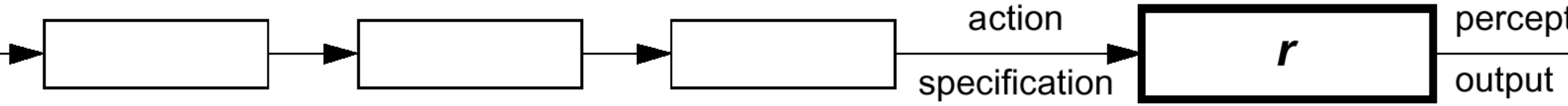


4-level temporal decomposition

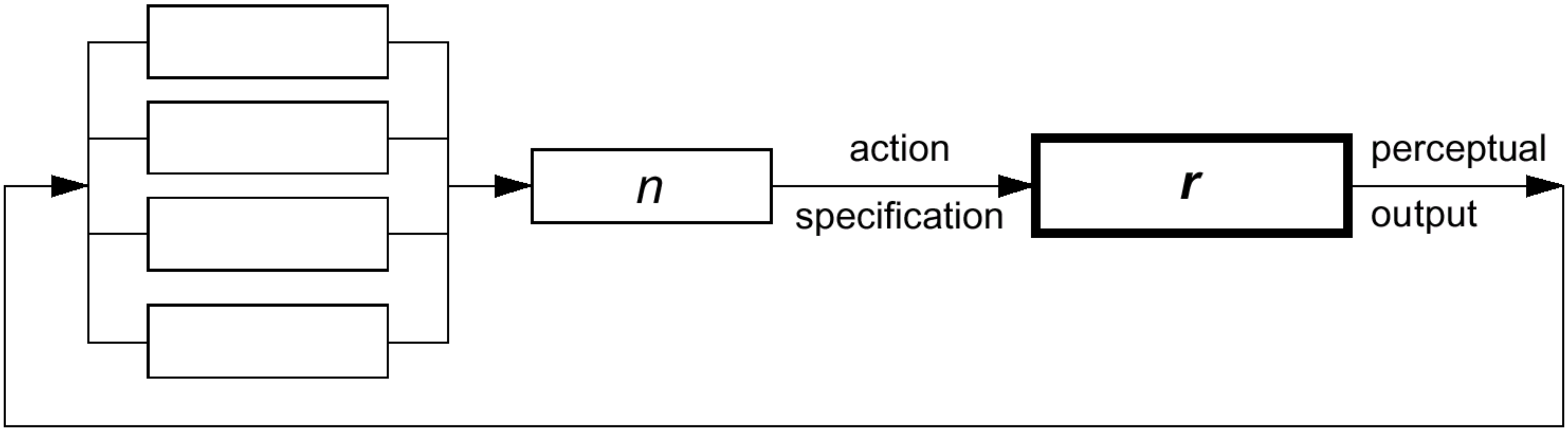


Control decomposition

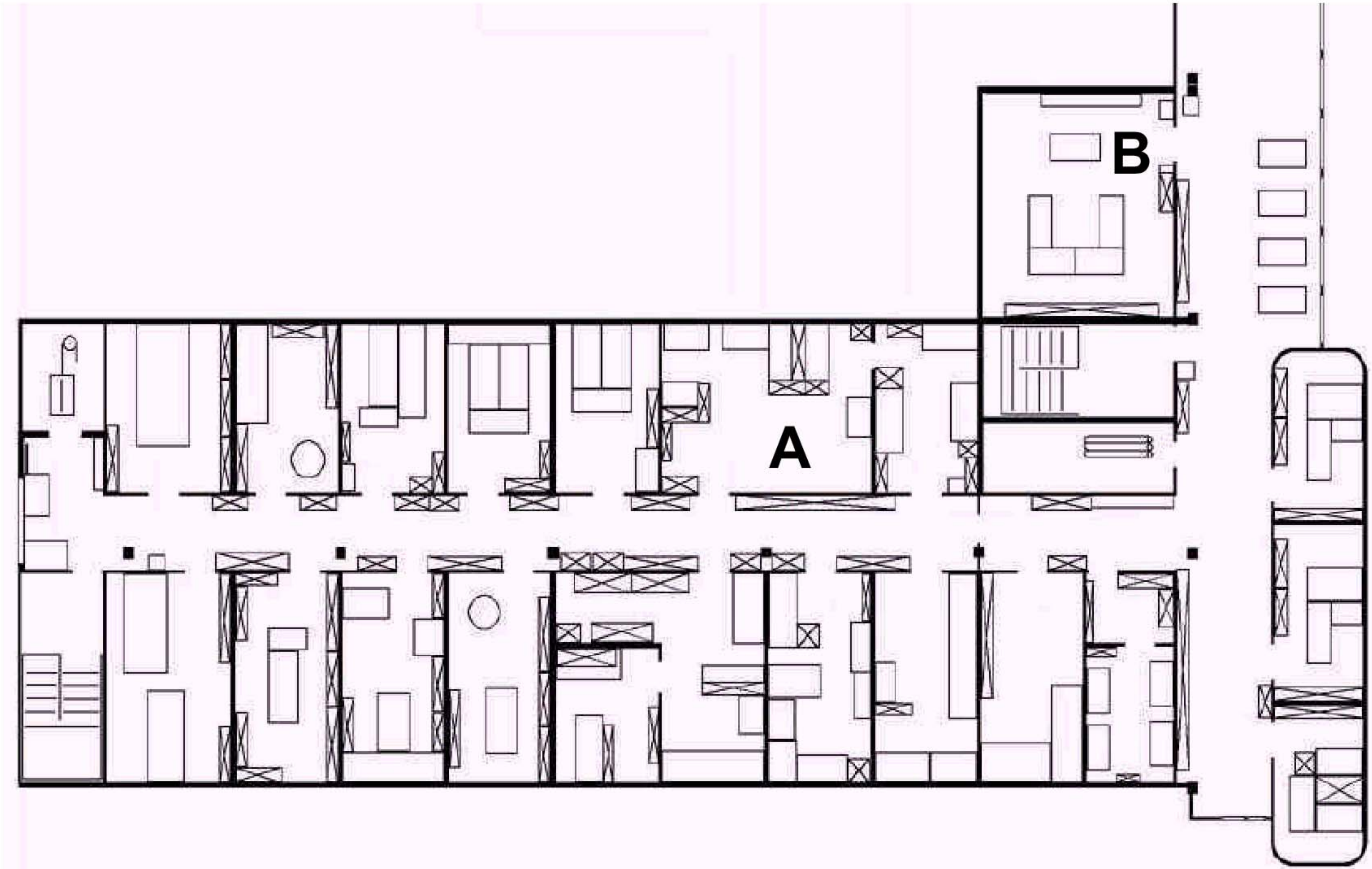
- Pure serial decomposition



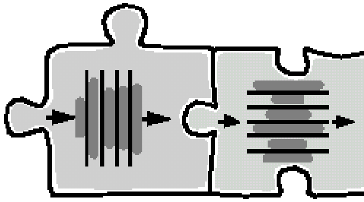
- Pure parallel decomposition

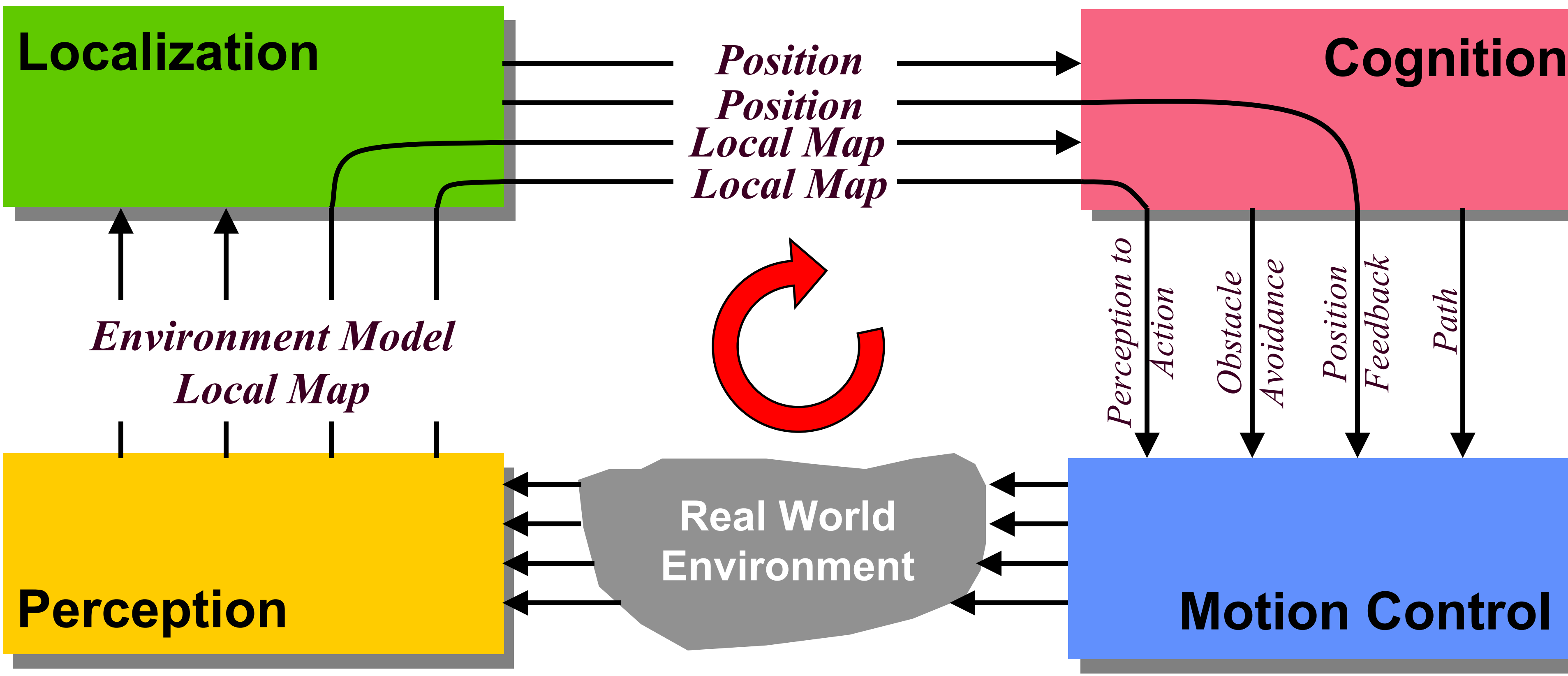


Sample Environment



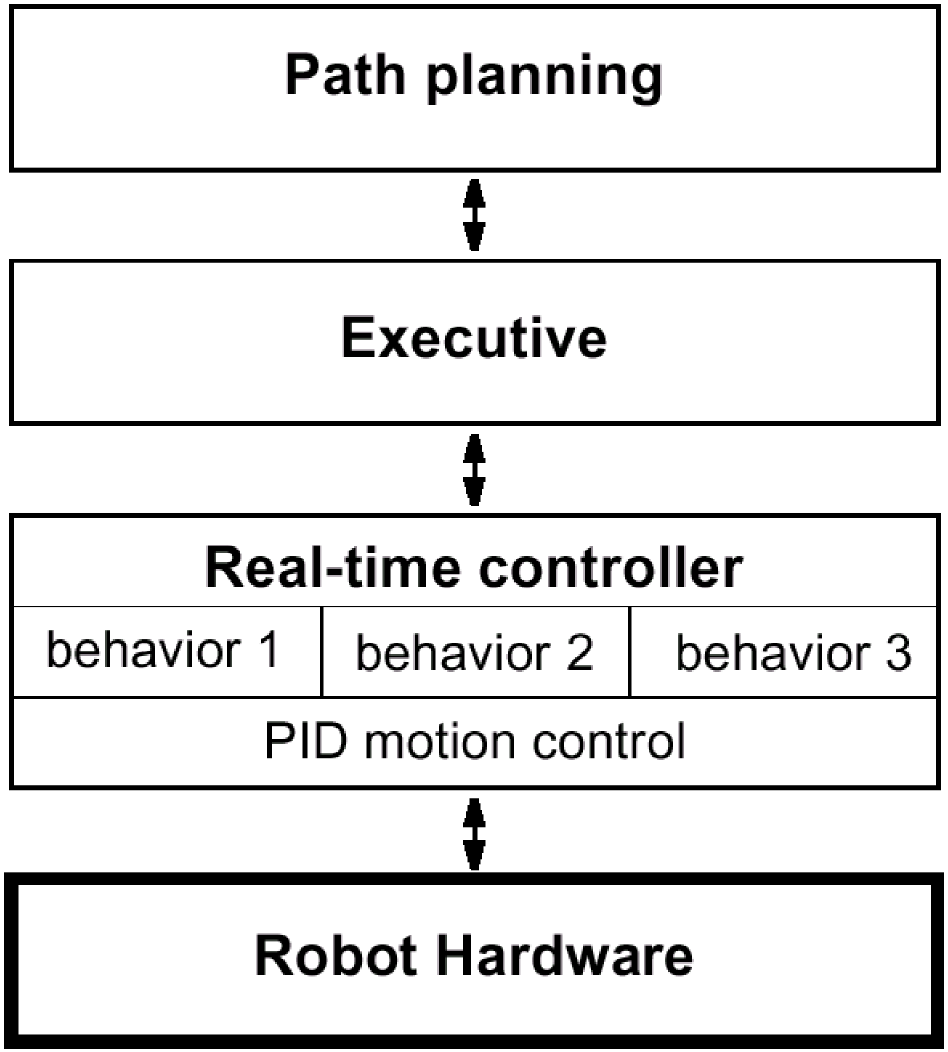
Our basic architectural example



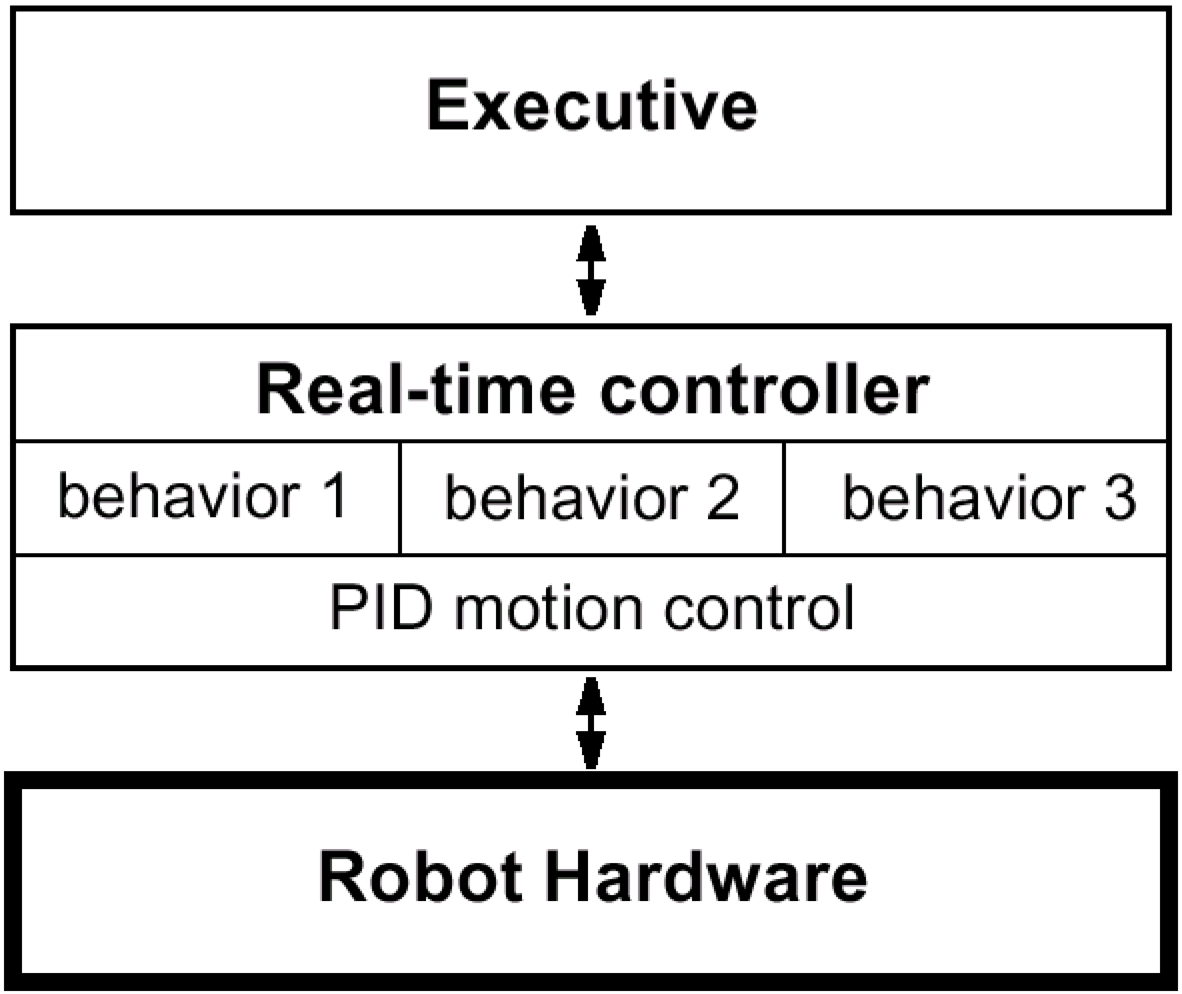


General Tiered Architecture

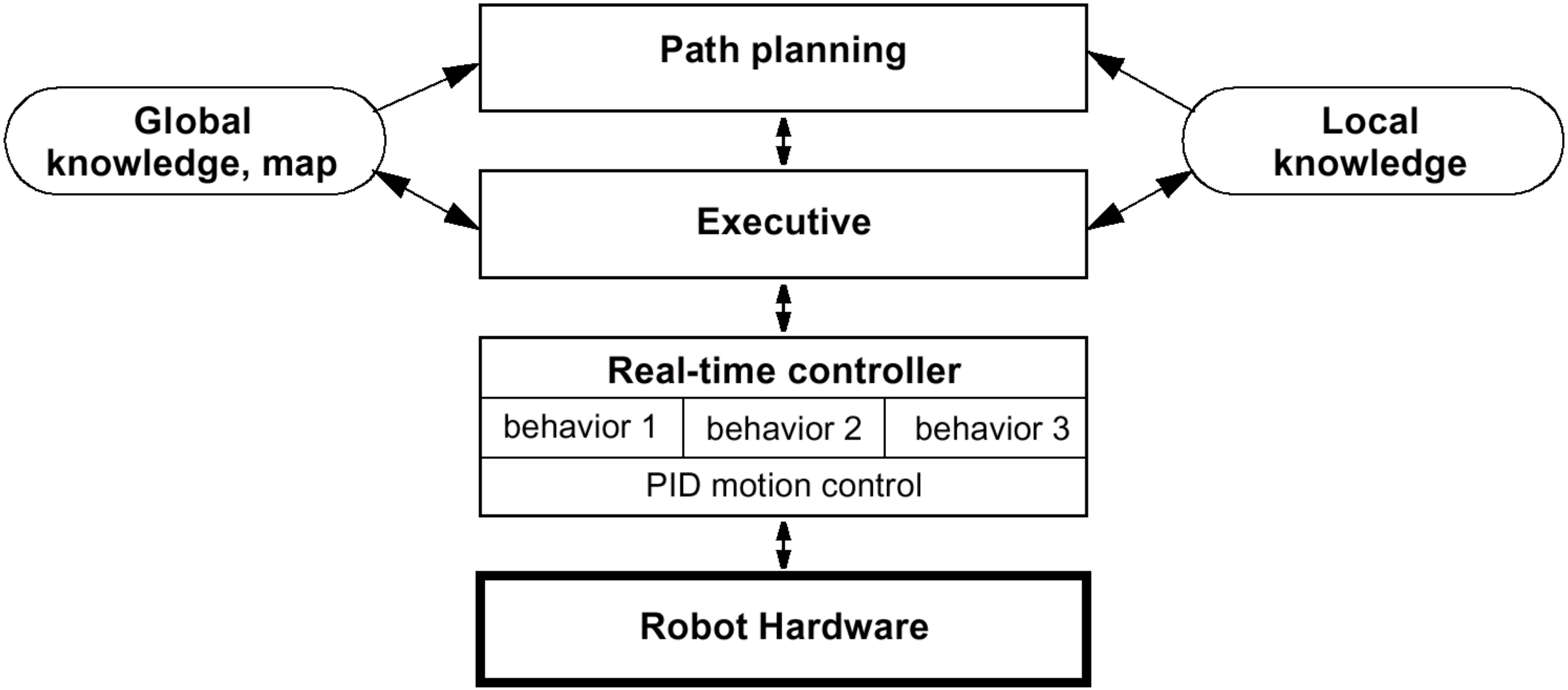
- Executive Layer
  - *activation of behaviors*
  - *failure recognition*
  - *re-initiating the planner*
- Deep Space One



A Two-Tiered Architecture for Off-Line Planning

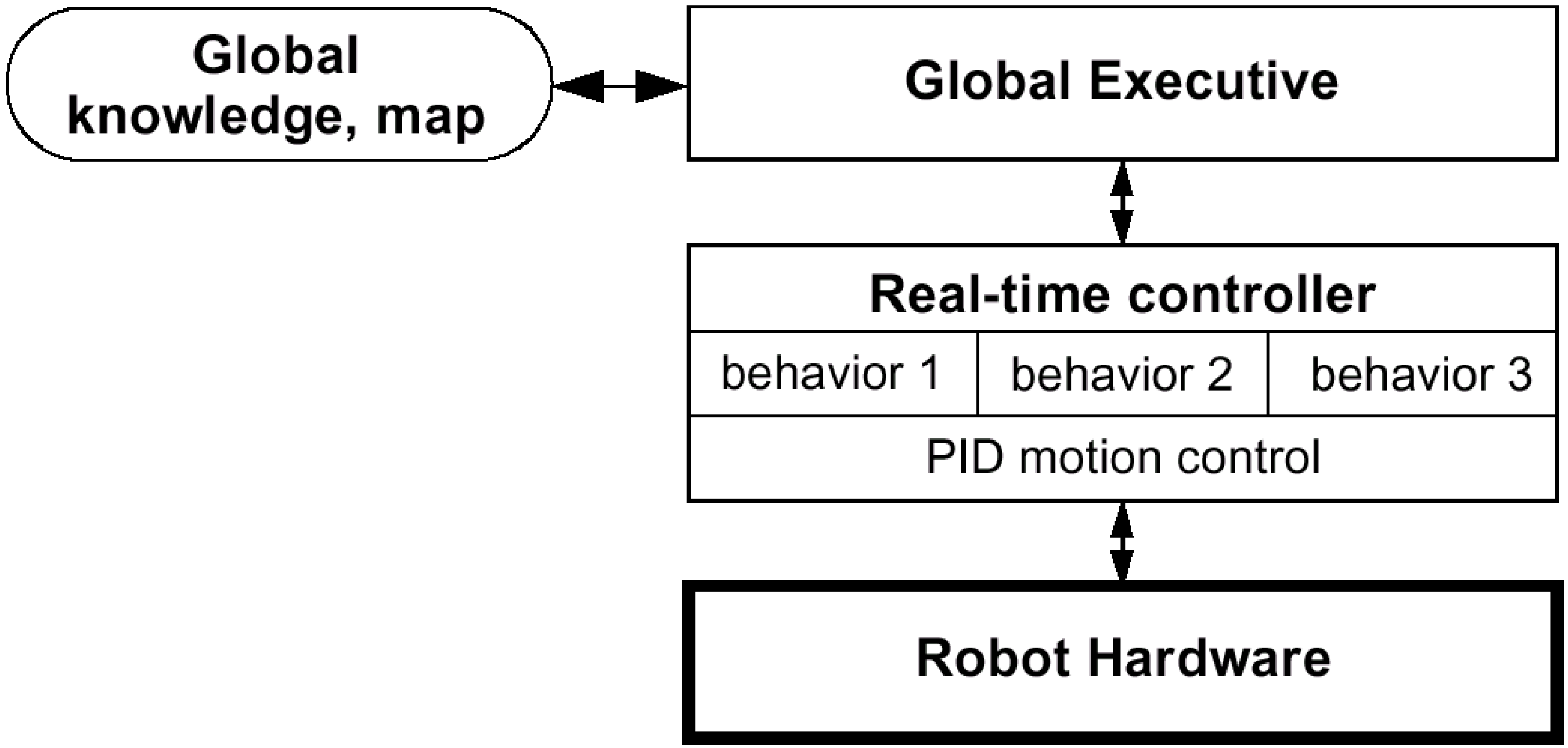


A Three-Tiered Episodic Planning Architecture.



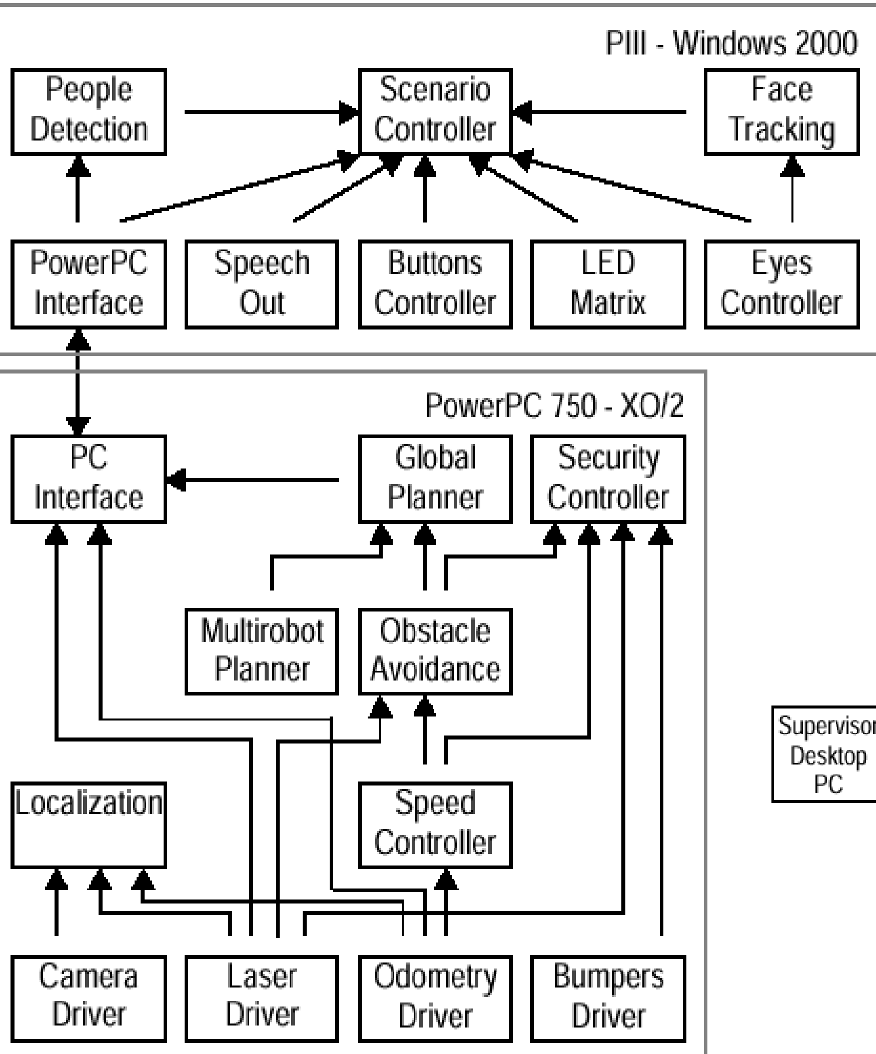
- Planner is triggered when needed: e.g. blockage, failure

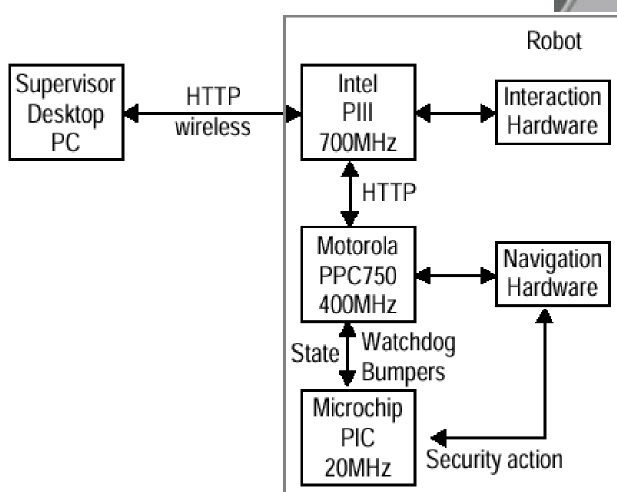
An integrated planning and execution architecture

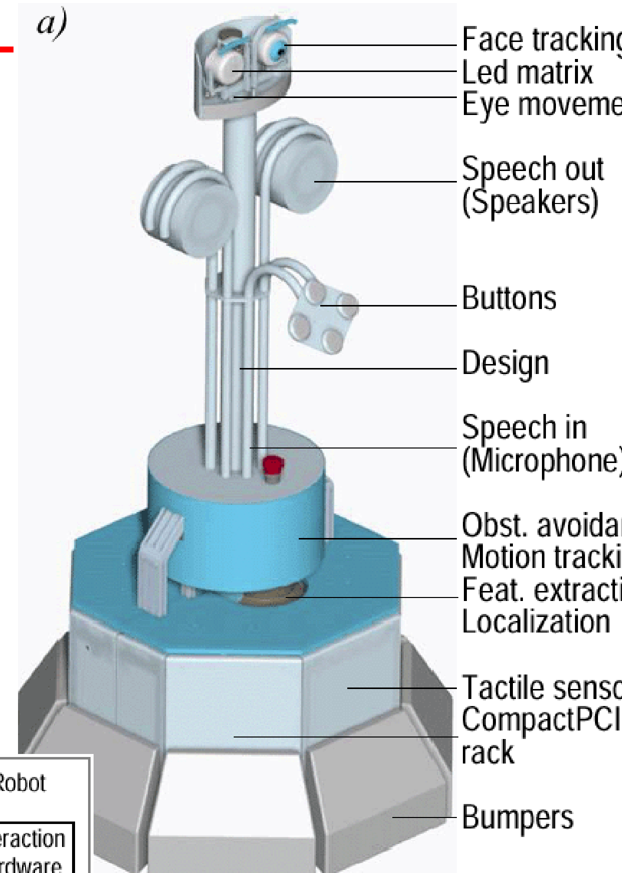


- All integrated, no temporal decomposition between planner and executive layer

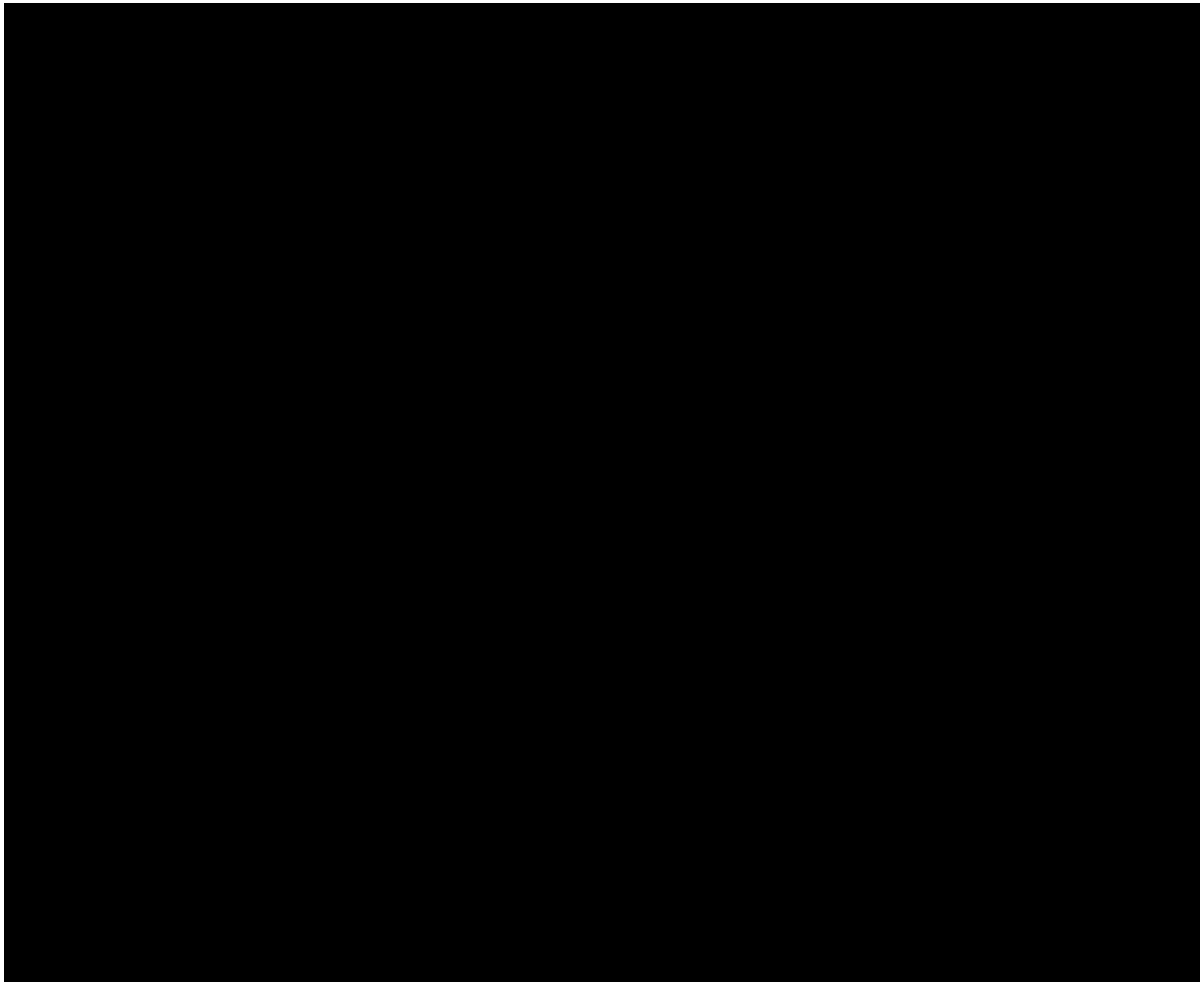
Example: The RoboX Architecture







Example: RoboX @ EXPO.02



Summary

- This lecture looked at:
  - *Path planning*
  - *Obstacle avoidance*
  - *Navigation*
- We revisited some of the map representations from previous lectures and showed how paths though these maps could be determined.
- We discussed obstacle avoidance, and described how obstacle avoidance techniques could be integrated into path execution.
  - *Combined, path planning, execution and obstacle avoidance equal navigation*
- Finally, we looked at robot control architectures and how they can implement navigation.