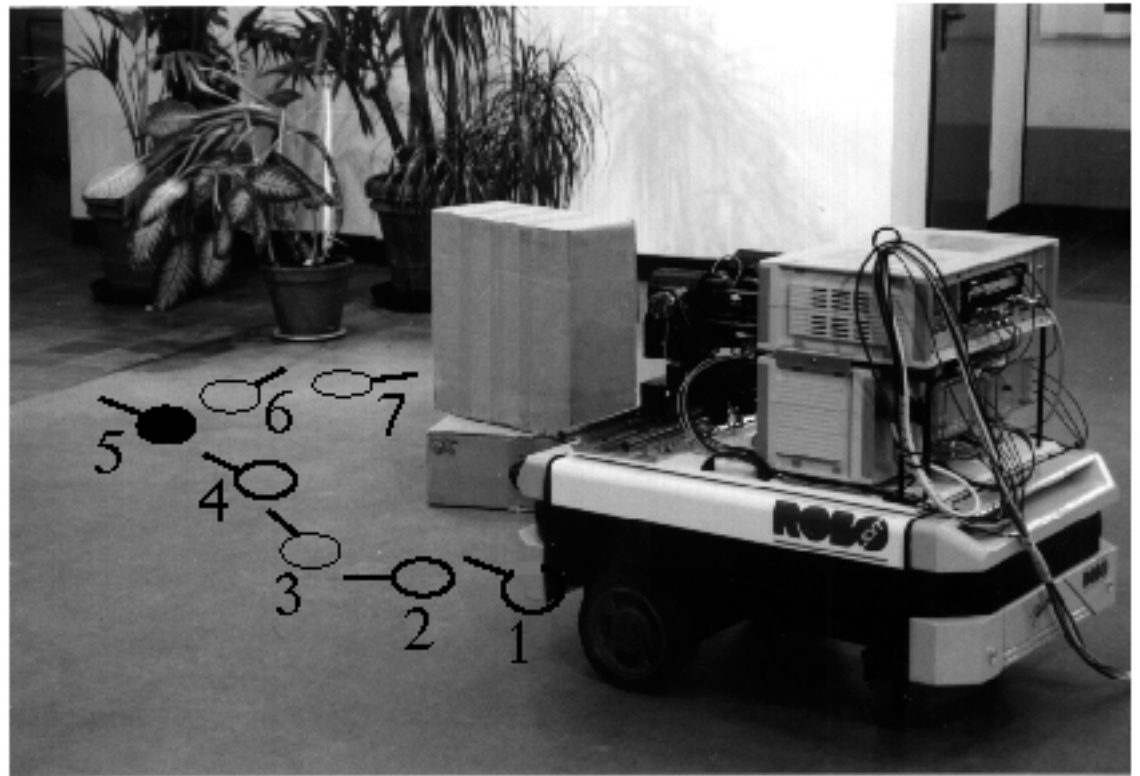


# Vehicle motion planning and control: Survey of approaches

Gregor Schöner

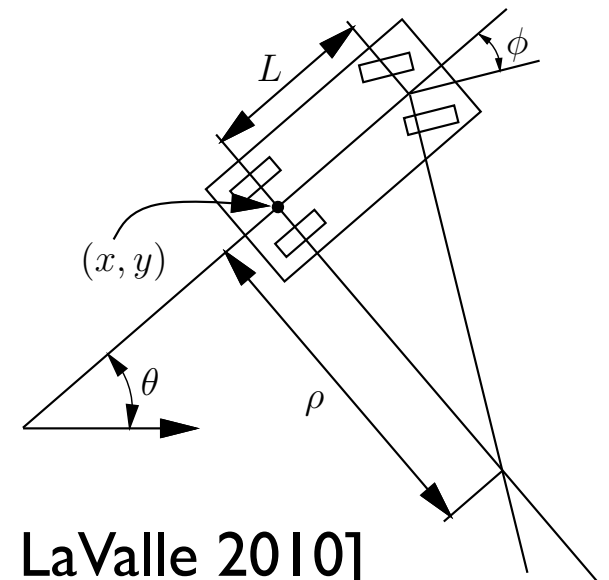
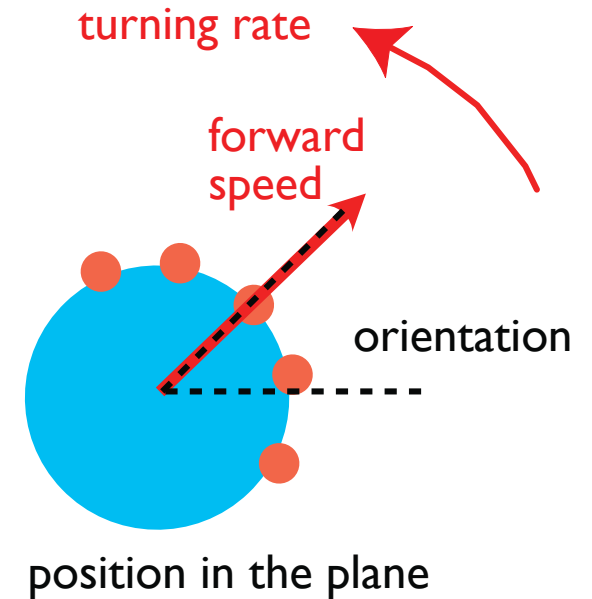
# The problem

- move about in a 2D world, which is occupied by objects/stuff
- constraints
  - reach targets
  - avoid collisions
  - via points
  - orientations



# Non-holonomic constraints

- Vehicles have typically non-holonomic constraints
- fewer variables can be varied freely (e.g. velocities chosen) than variables that describe the physical state
- state depends on the history of movement



[from LaValle 2010]

# What is needed to autonomously move in an environment?

- sense something about the environment
- know about the environment
- plan movement in the environment that is collision-free
- control vehicle to achieve planned movement
- estimate what vehicle actually did

# Concepts for planning

## ■ local vs. global

- planning based on information only about the local environment of the robot
- vs. based on global map information about the environment

## ■ reactive vs. planning

- motion planning “on the fly” in response to sensory inputs
- vs. motion planning for an entire action from initial to goal state

# Concepts for planning

## ■ exact vs. heuristic

- exact: guarantee that a path that fulfills the constraints is found when one exists
- vs. generate a plan based on ad hoc approach that is likely to fulfill constraints

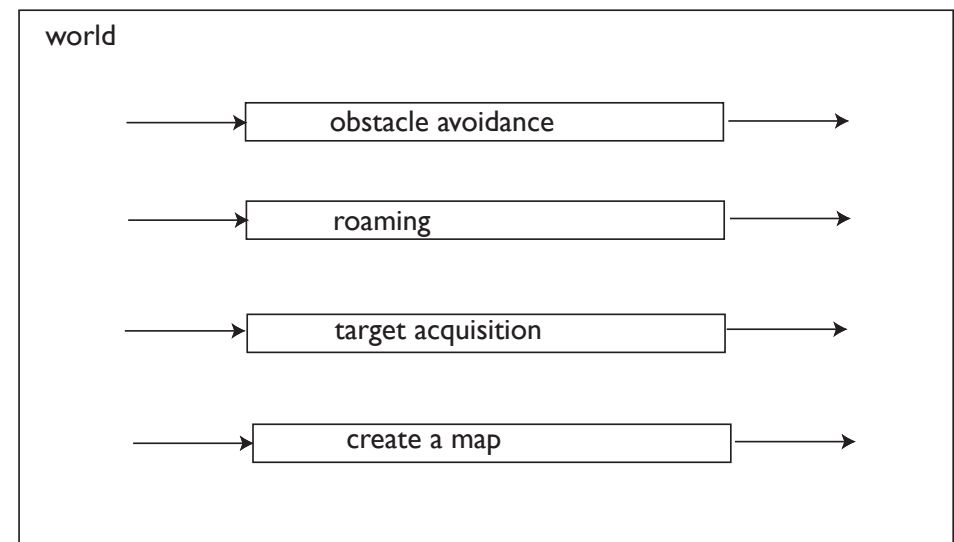
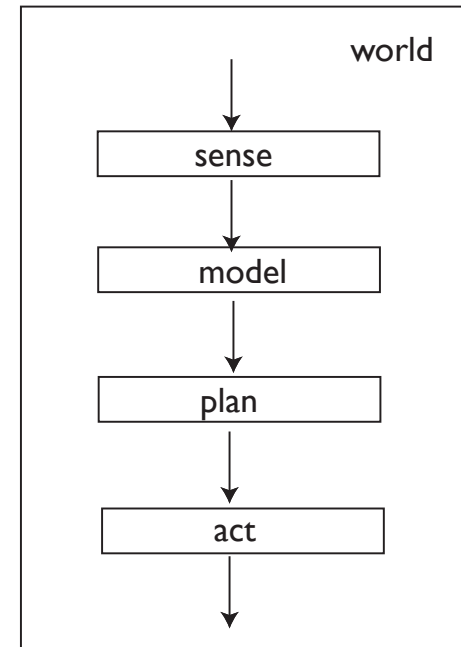
## ■ continuous vs. discrete:

- continuous state space variables
- vs. grid state spaces, graph state spaces

# Concepts for planning

## ■ sense-plan-act vs behavior-based

- based on world representation that informs all planning
- vs. based on low-level sensory information that is specific to each individual behavior, planning emerges from how behaviors interact



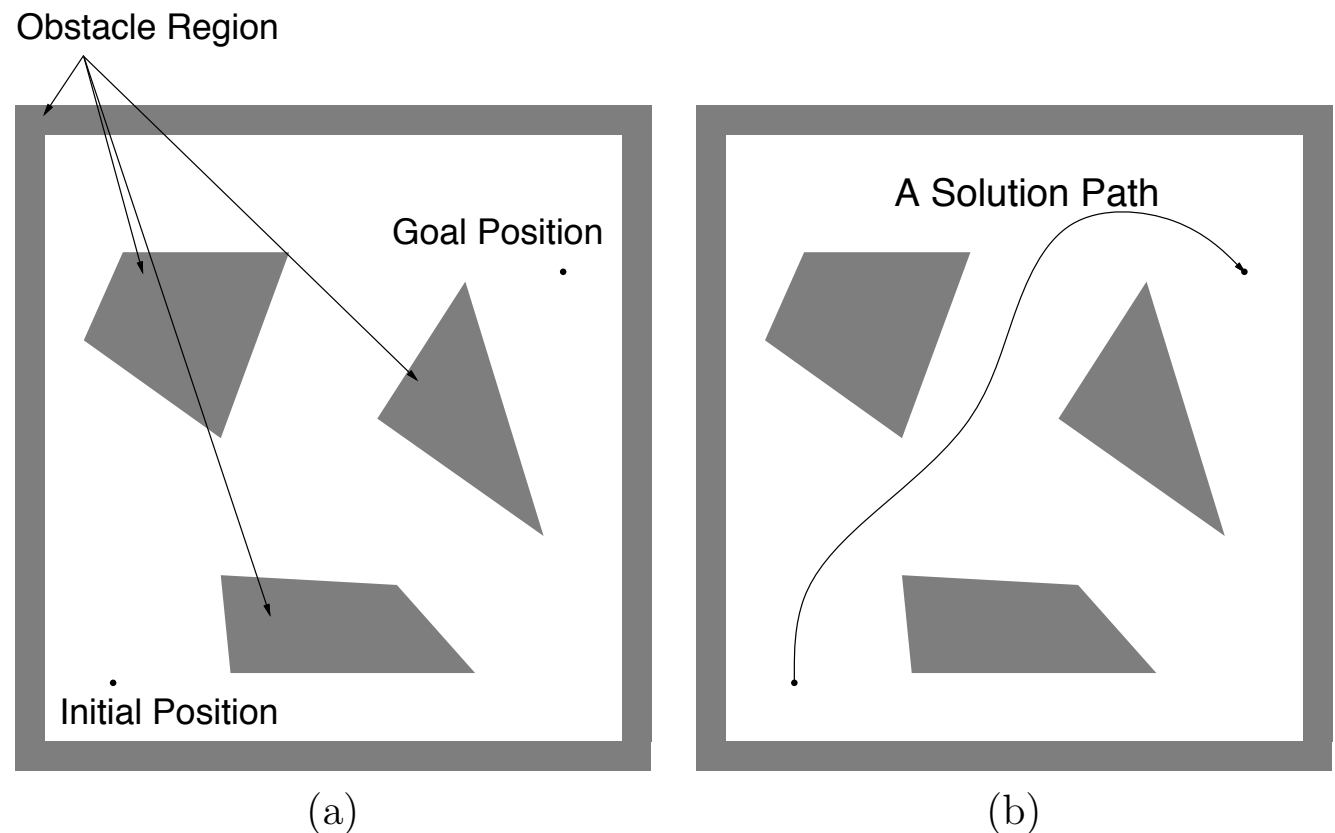
# Approaches to vehicle path planning

- classical planning approaches
- potential field approach
- Borenstein & Koren
- (dynamic window approach)

# Classical global path planning

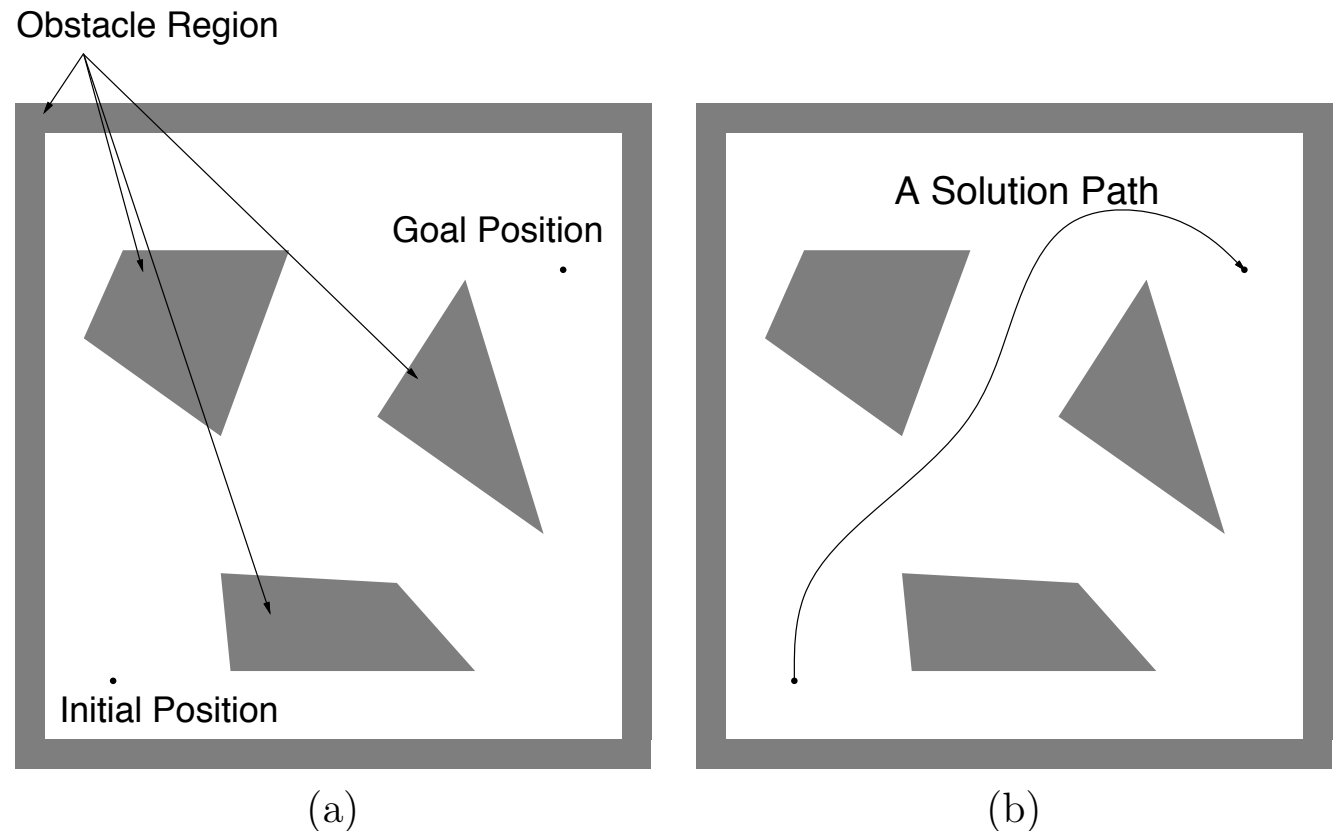
- standard reference: Latombe: Robot motion planning, 1991
- very good general review: LaValle: Planning algorithms, 2006, 2010

[LaValle, 2006]



# Classical global path planning

- mathematical theories of constraint satisfaction and decision theory
- searching spaces, sampling approaches



[LaValle, 2006]

# Classical local path planning

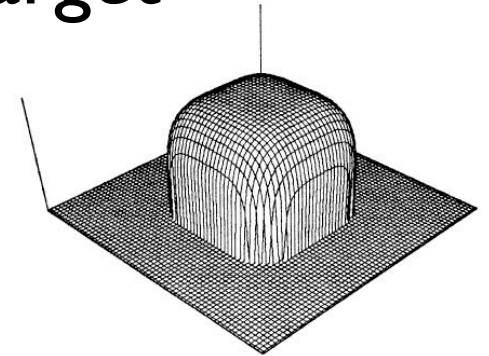
- reference: Cox, Wilfong: Autonomous Robot Vehicles, 1990
- based on a known world (e.g., represented as a polygonal model of surfaces)
- taking into account a kinematic model of the vehicle
- add smoothness constraints

# Potential field approach

- invented by Khatib, 1986 (similar earlier formulation: Neville Hogan's impedance control)
- the trajectory of a manipulator or robot vehicle is generated by moving in a potential field to a minimum
- the manipulator 3D end-position or vehicle 2D position is updated by descending within that potential field
- obstacles are modeled as hills of potential field; target states are valleys/minima of the potential field

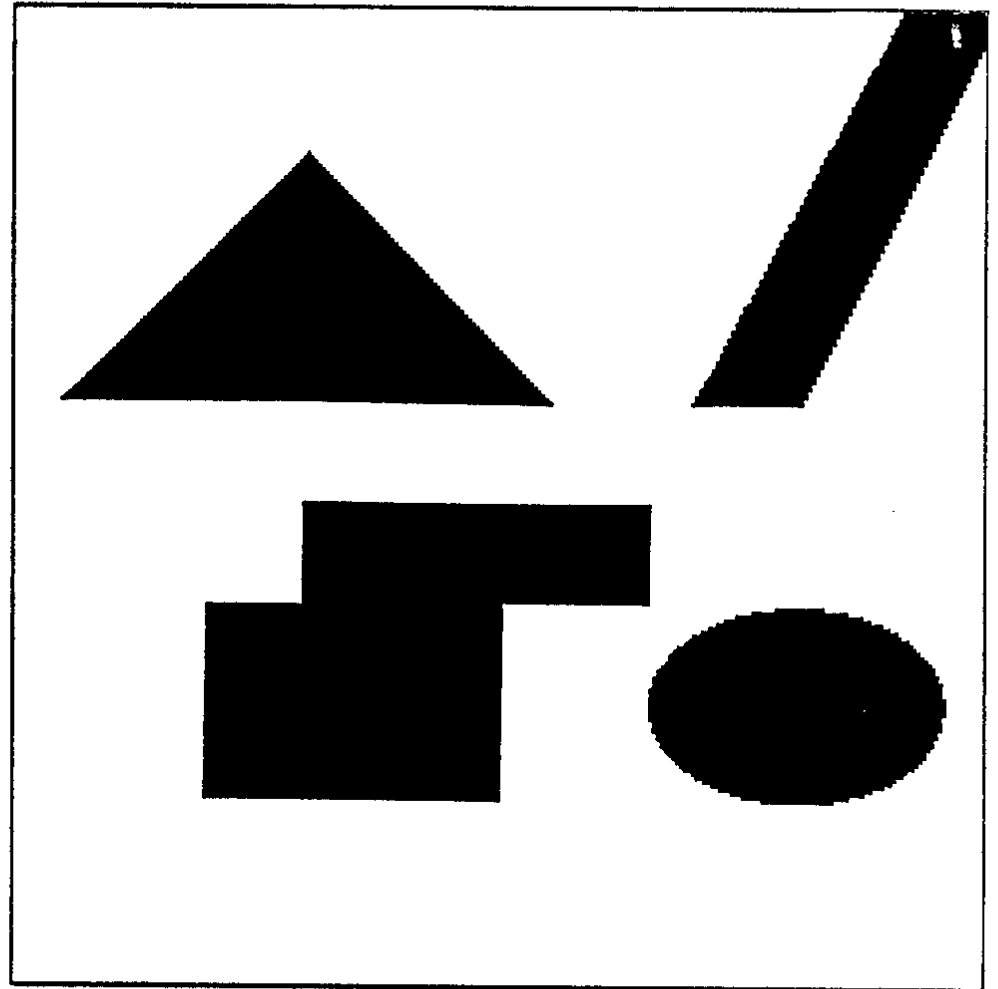
# Potential field approach as a heuristic planning approach

- need a mathematical representation of target and obstacle configuration
- make potential minimum at target
- make potential maximum at obstacles
- compute downhill gradient descent for path generation



# Potential field approach

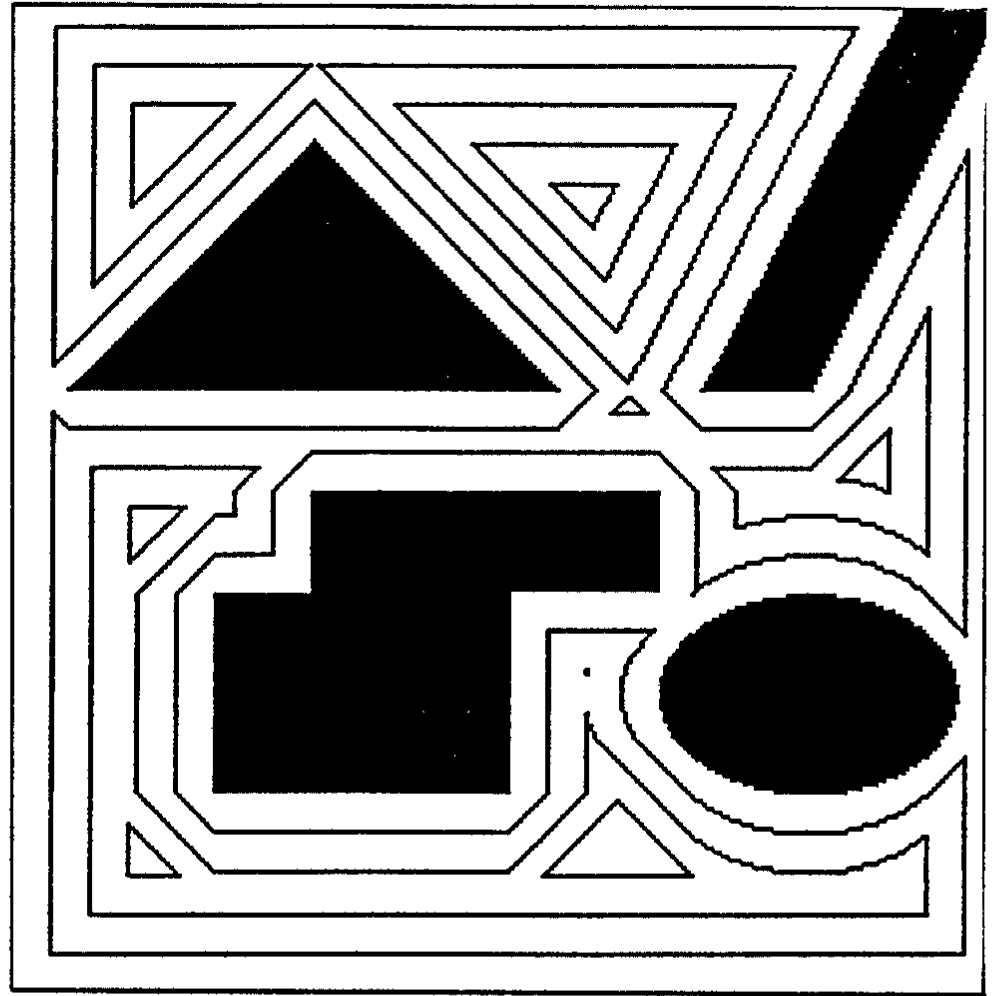
■ obstacle  
configuration



[Barranquand, Langlois, Latombe, 1989]

# Potential field approach

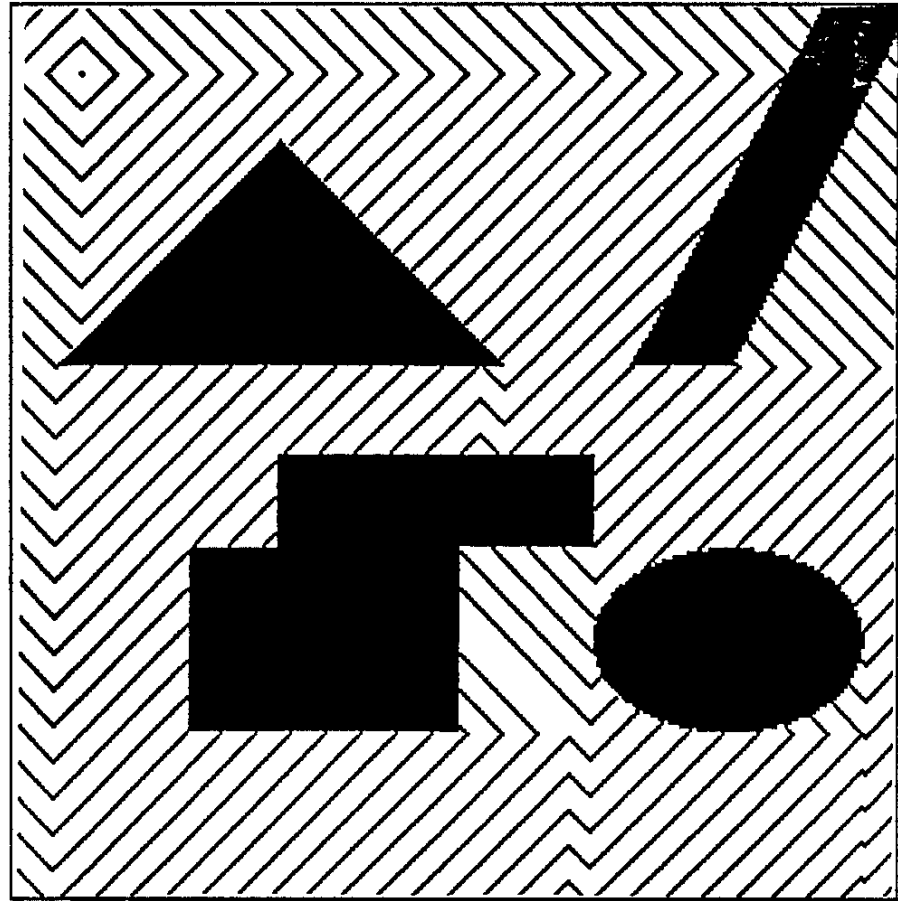
- contours of associated obstacle potential field



[Barranquand, Langlois, Latombe, 1989]

# Potential field approach

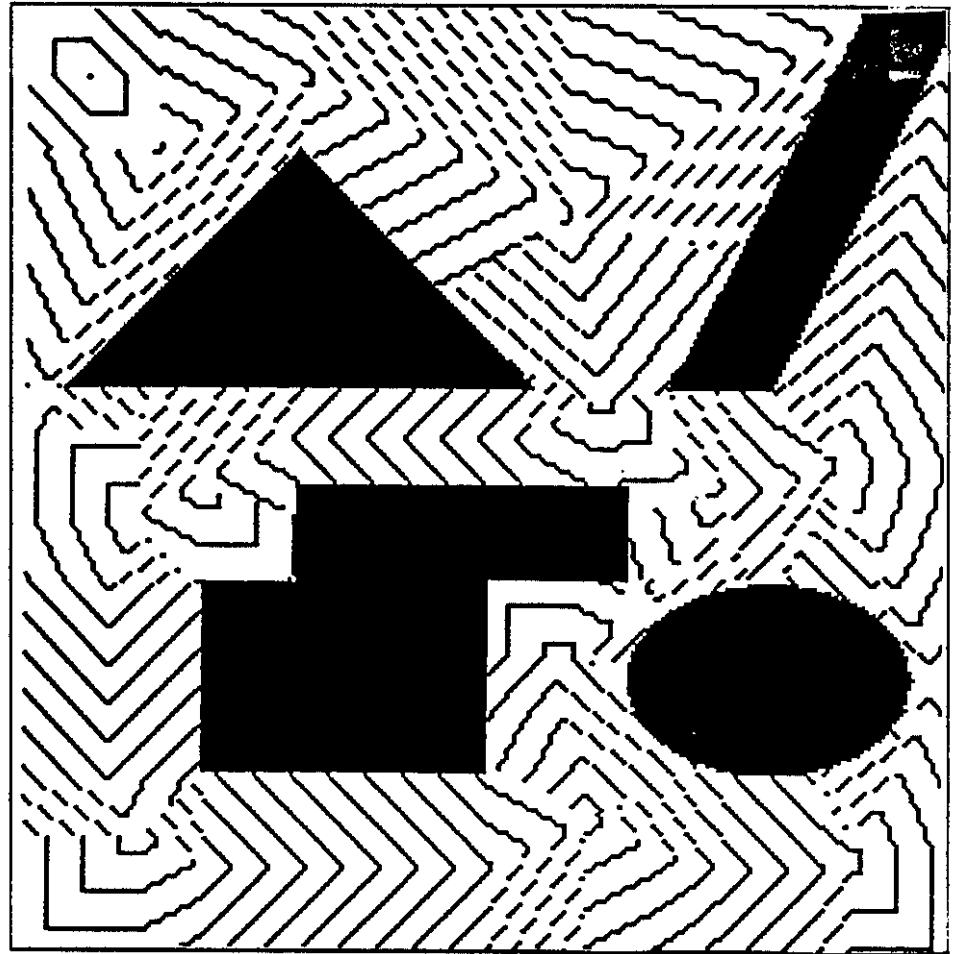
■ contours of  
target potential  
field



[Barranquand, Langlois, Latombe, 1989]

# Potential field approach

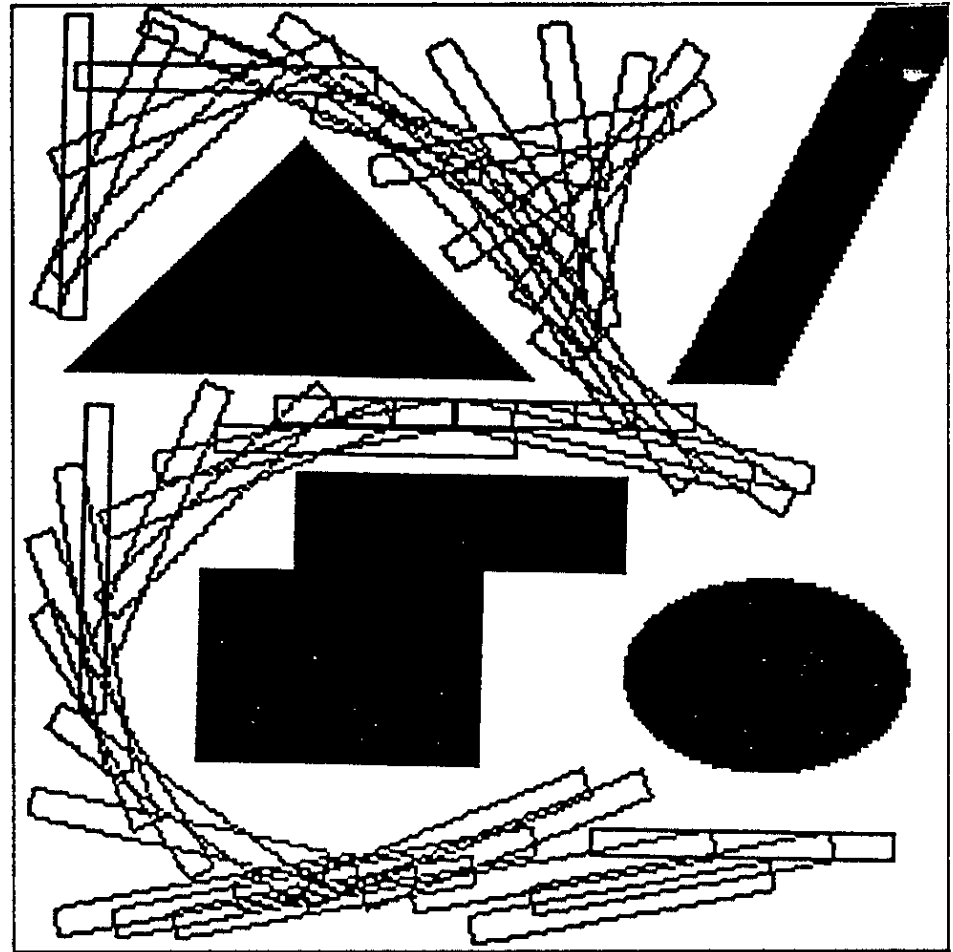
- contours of improved target potential field (by adding bubbles around obstacles)



[Barranquand, Langlois, Latombe, 1989]

# Potential field approach

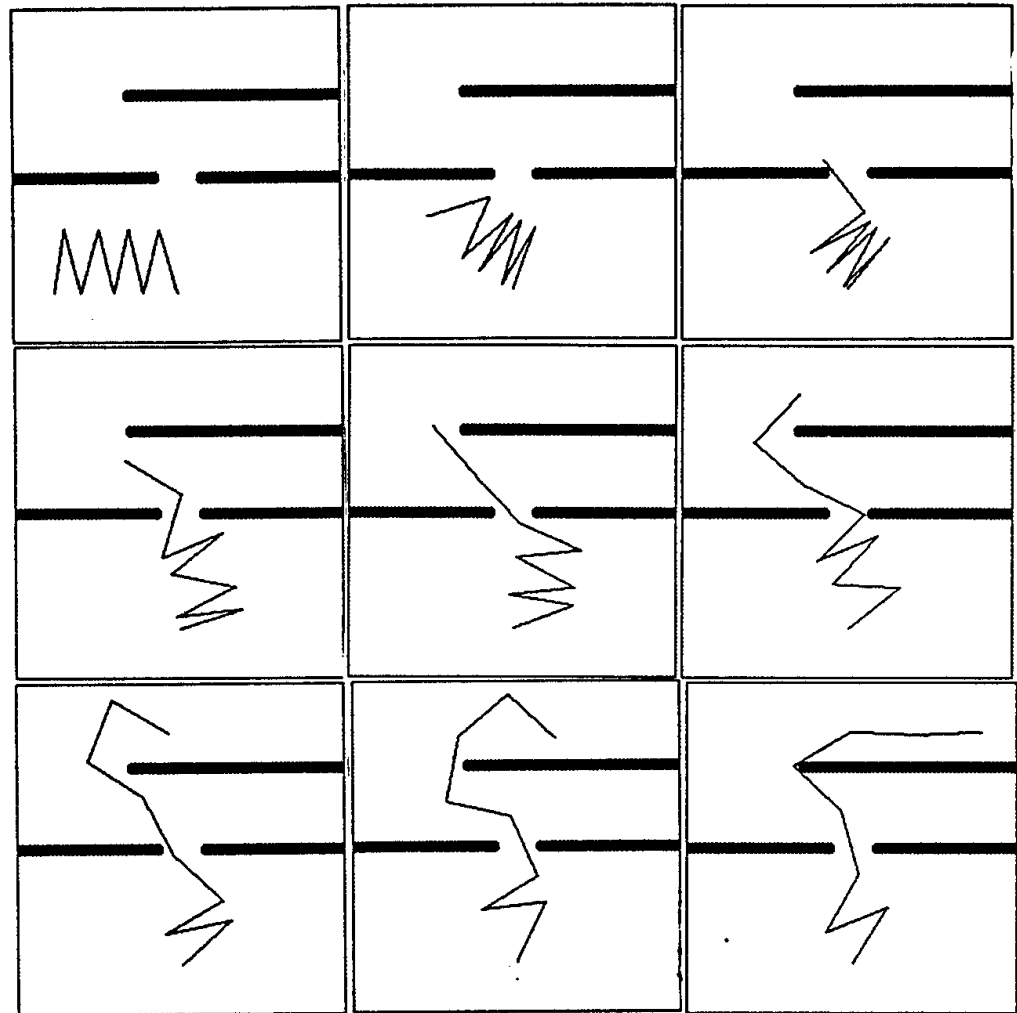
- adding all contributions leads to solution: gradient descent for vehicle



[Barranquand, Langlois, Latombe, 1989]

# Potential field approach

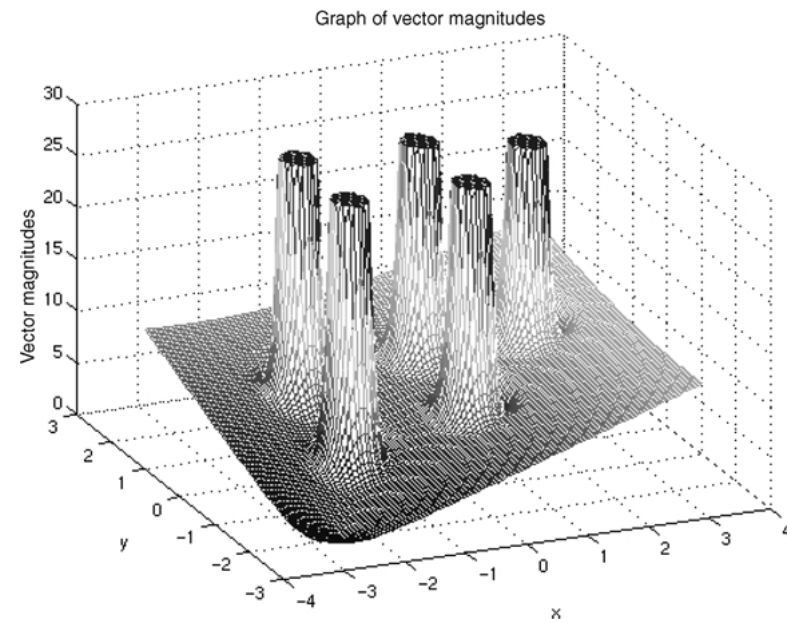
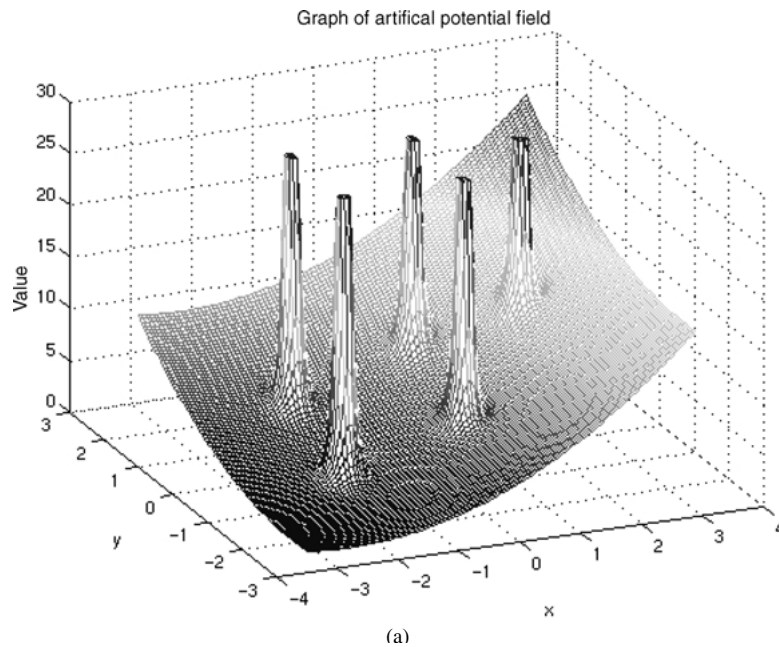
- generalization to higher-dimensional configuration spaces



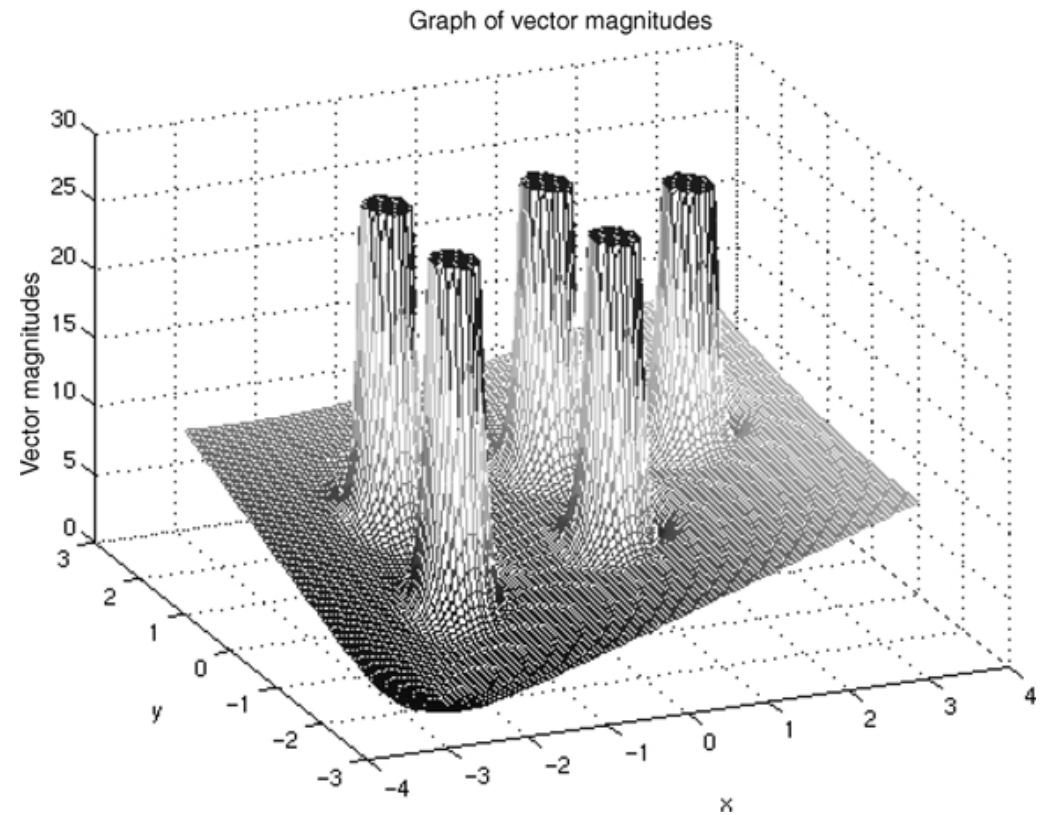
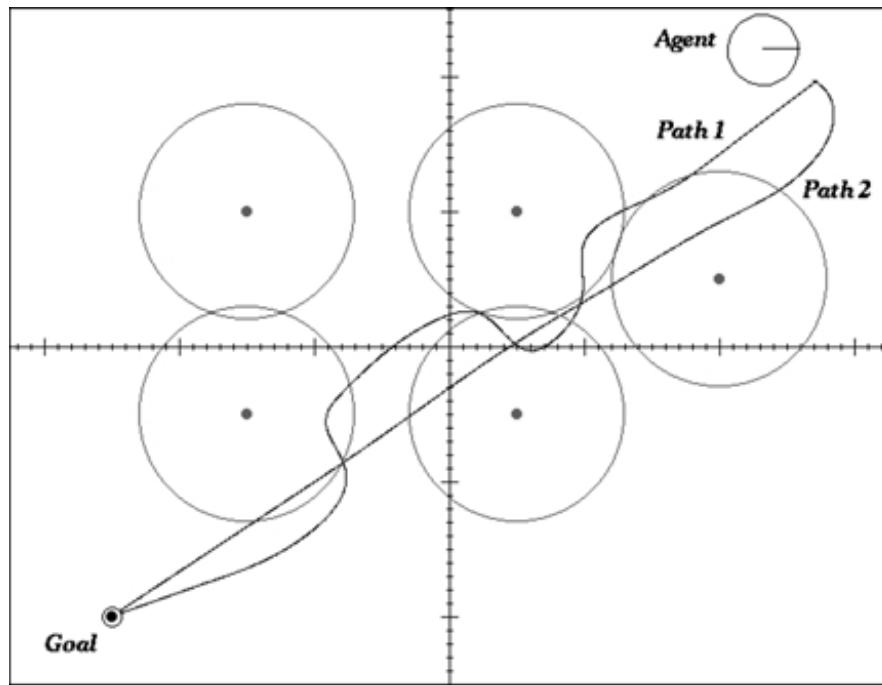
[Barranquand, Langlois, Latombe, 1989]

# Comparison to human behavior

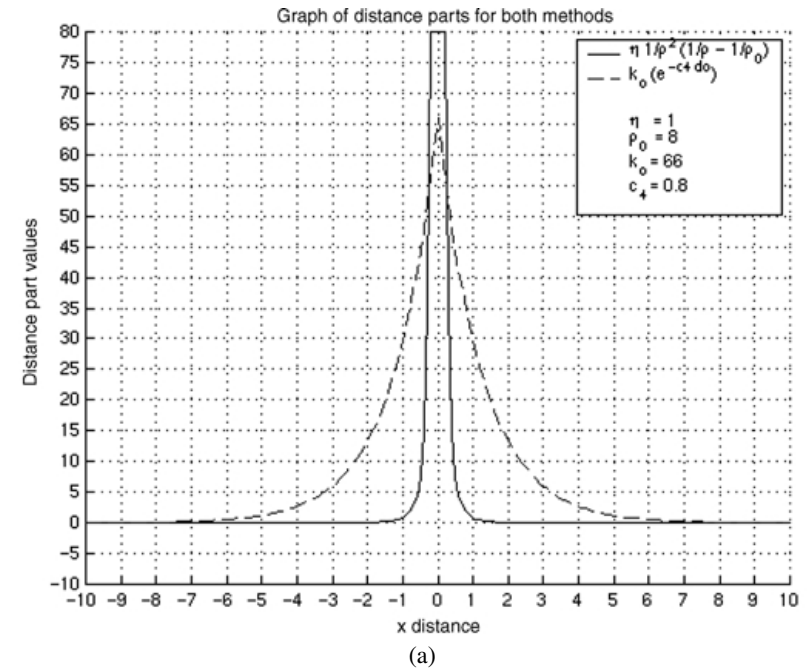
- Fajen/Warren compared the fit of a potential field approach to the fit of the attractor dynamics approach of human locomotion data



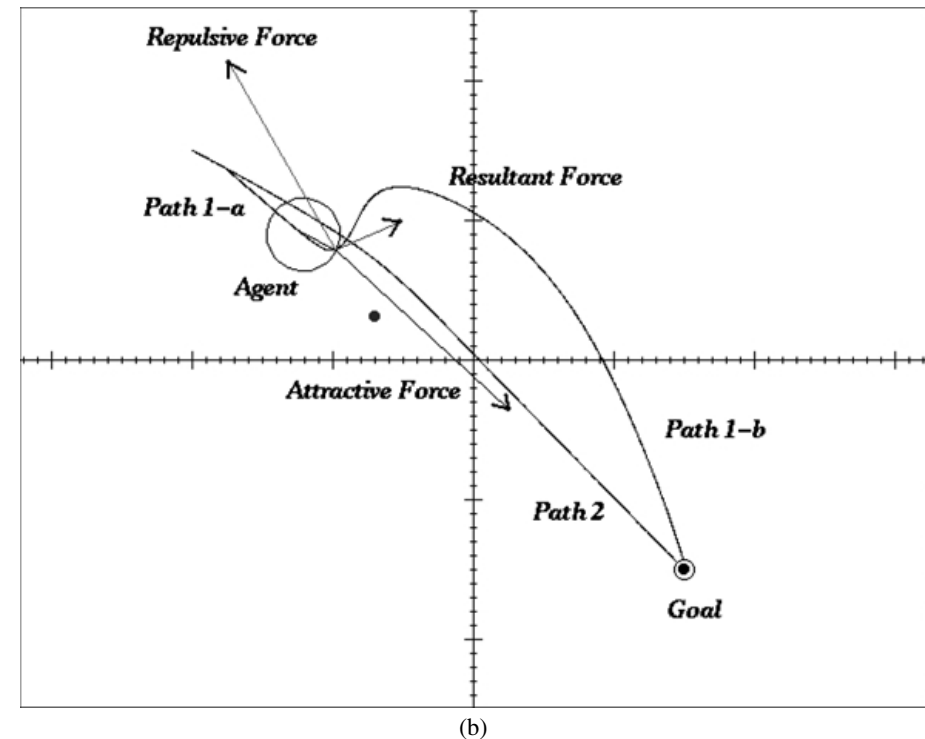
# Comparison to human behavior



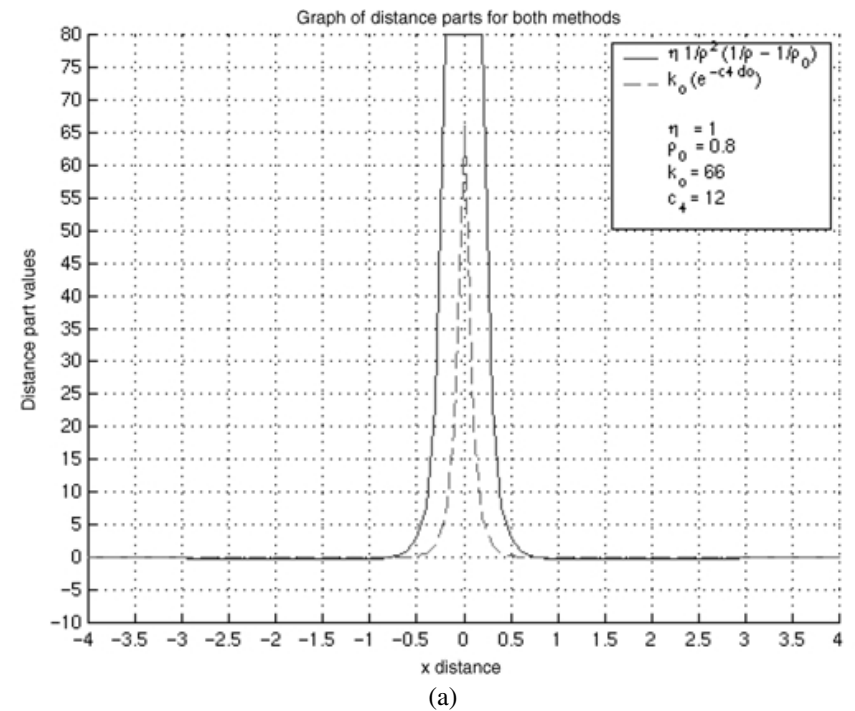
# comparison potential field vs. attractor dynamics



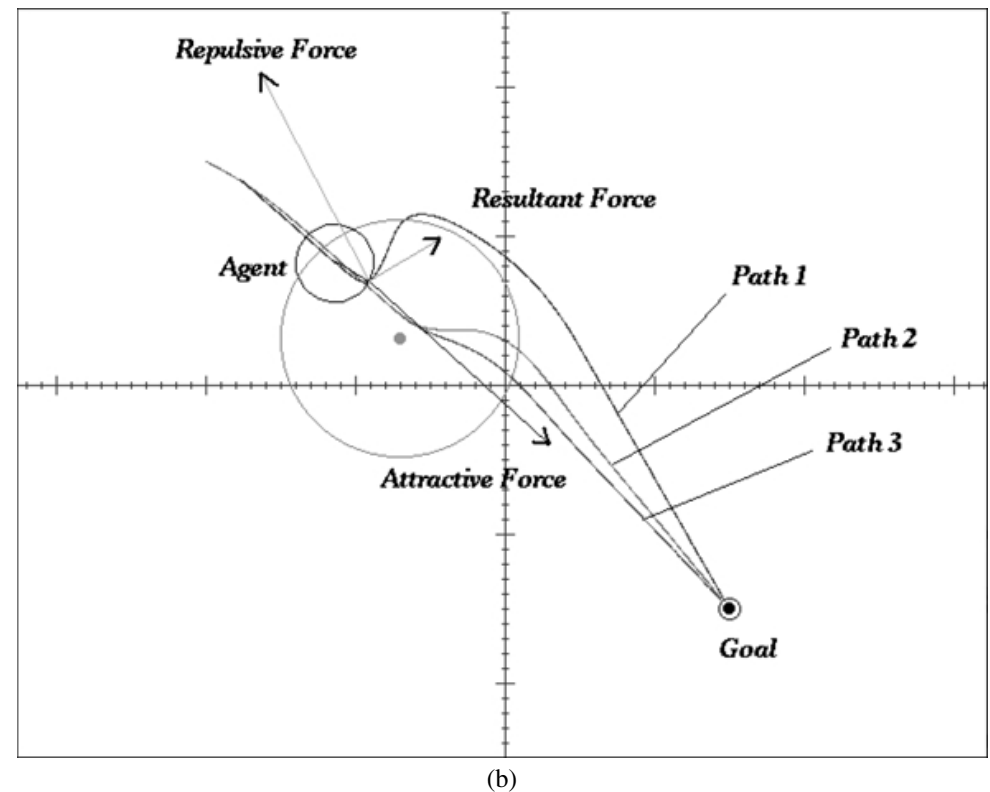
- potential sharper than distance dependence of repellor



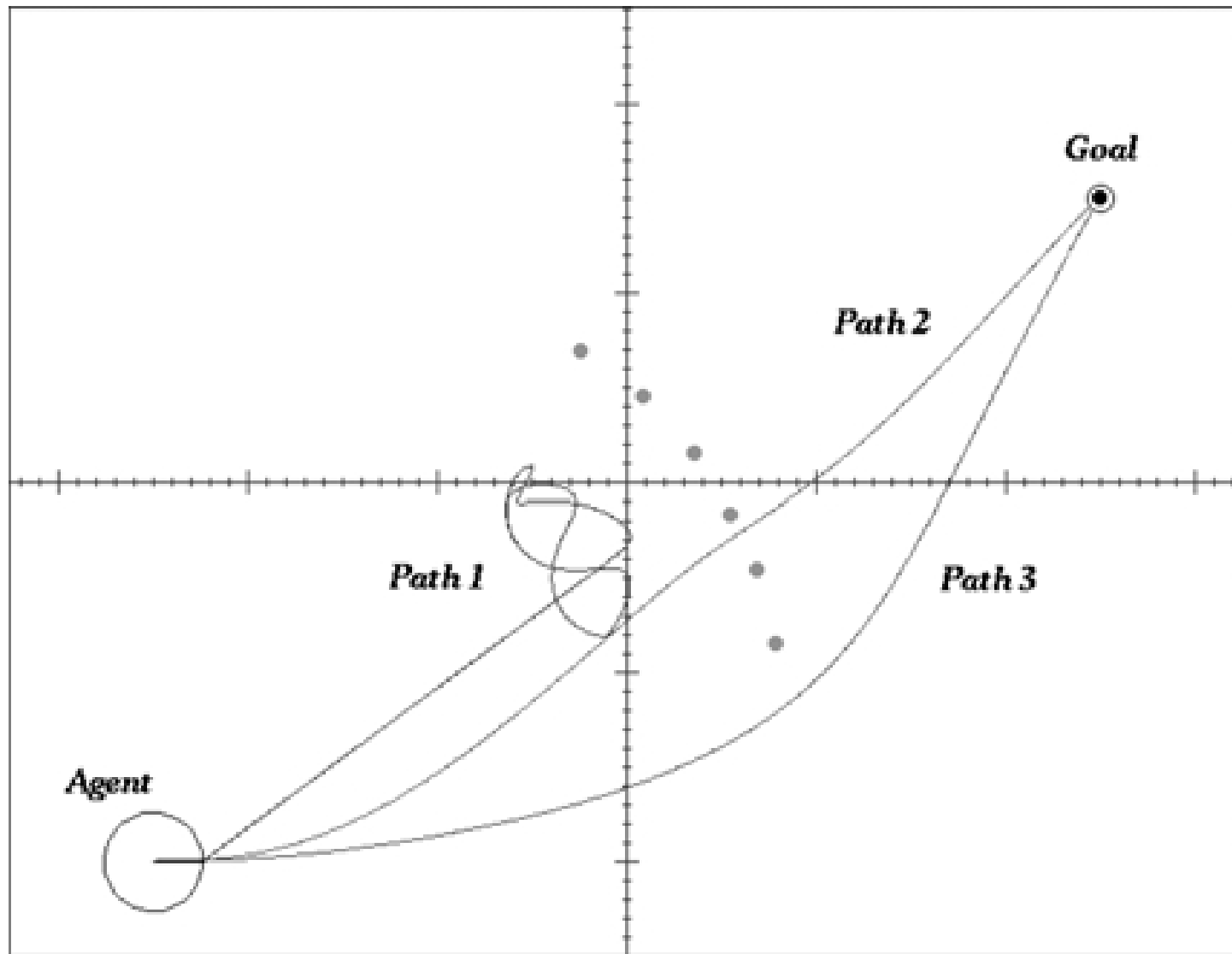
# comparison potential field vs. attractor dynamics



- potential softer than distance dependence of repeller



# spurious attractors in potential field approach



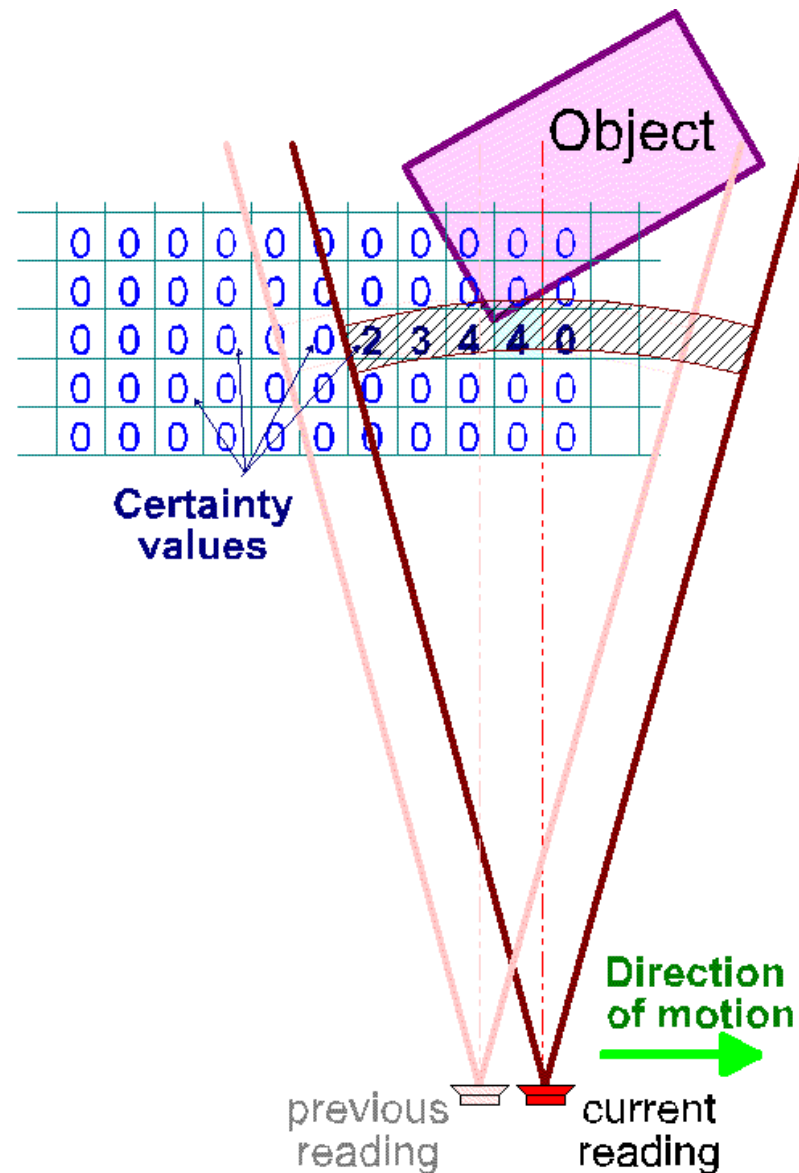
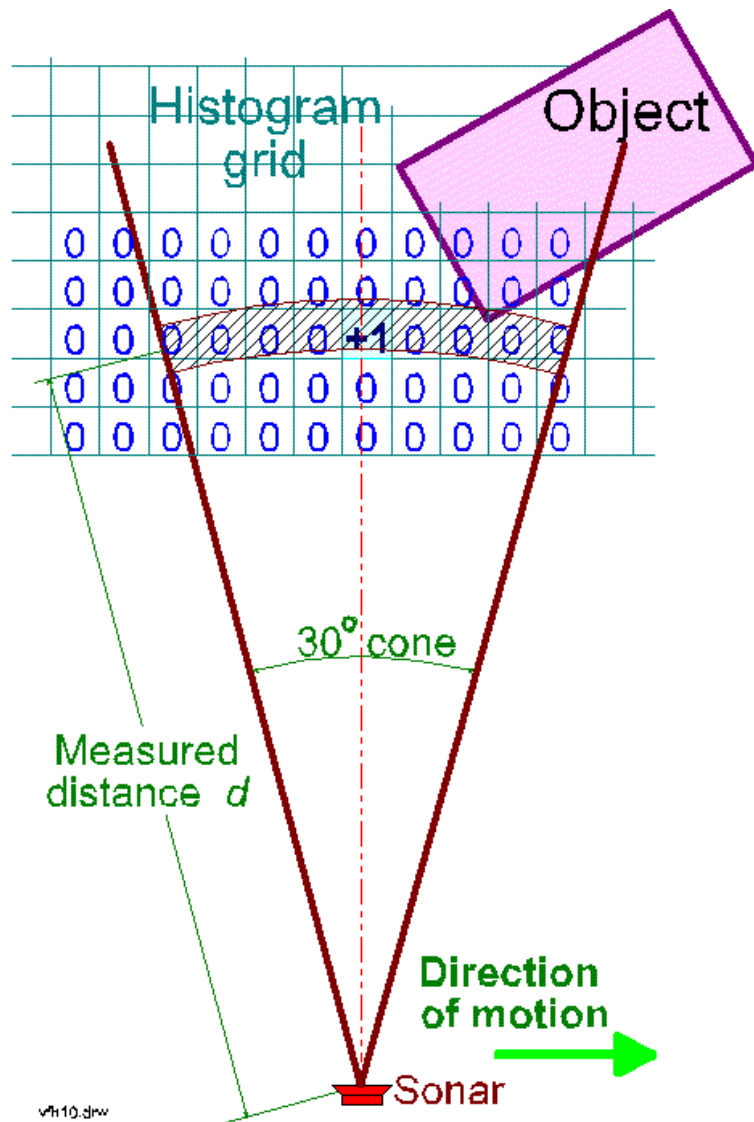
# Potential fields: limitations

- spurious attractors and constraint violations
- solution: making potential field approach exact and global: navigation functions
- potential computed such that it only has the right maxima and minimal
- but: computational cost
- but: requires global information

# Virtual force field: Borenstein & Koren

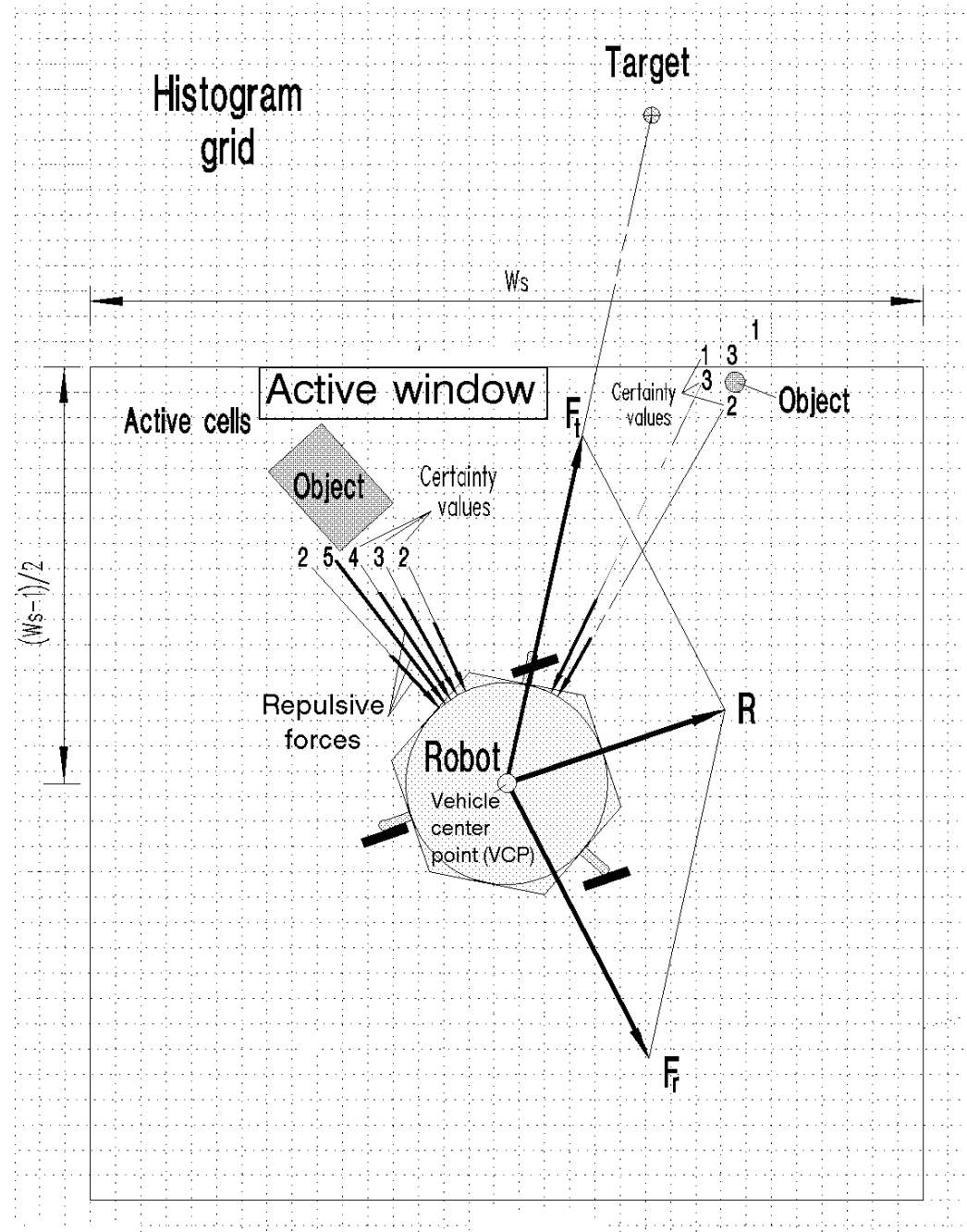
- ultra-sound histograms: the virtual force field concept
- vector-field histogram concept: polar histogram (heading direction!); height (strength) depends on both certainty and distance
- threshold: determine free sectors
- select free direction closest to target

www.101hv



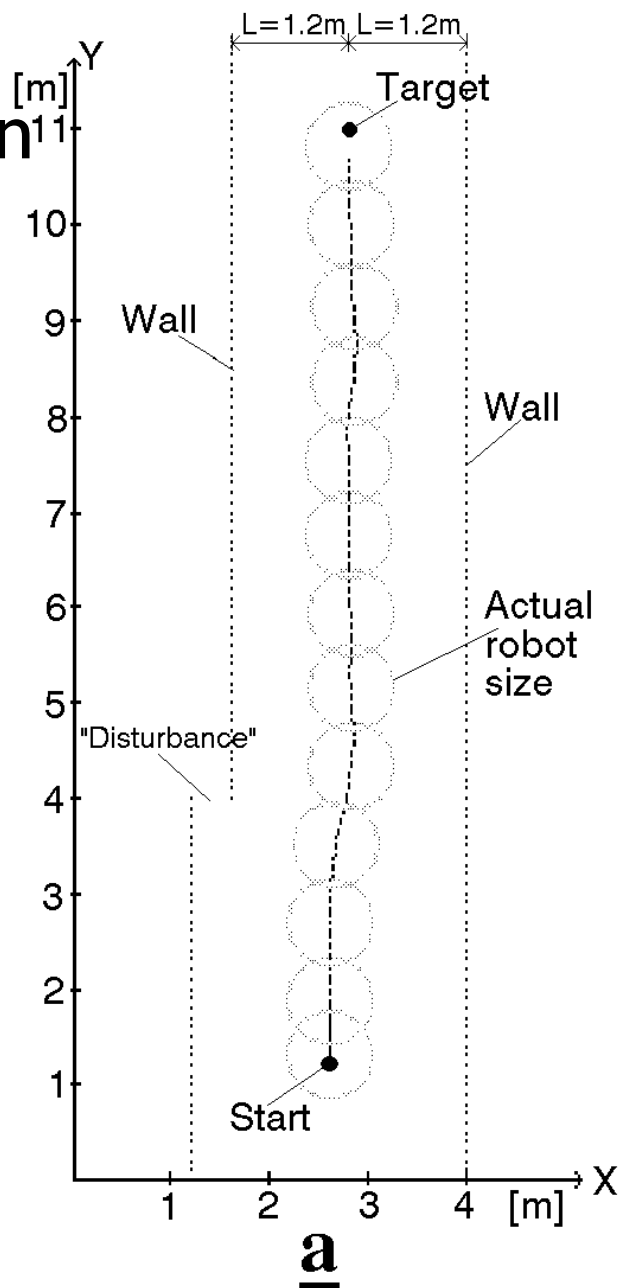
# Virtual force field: Borenstein & Koren

- vector toward target
- active window around robot
- use histogram within active window to compute vectors pointing away from obstacle
- vector summing
- ~dynamic approach!

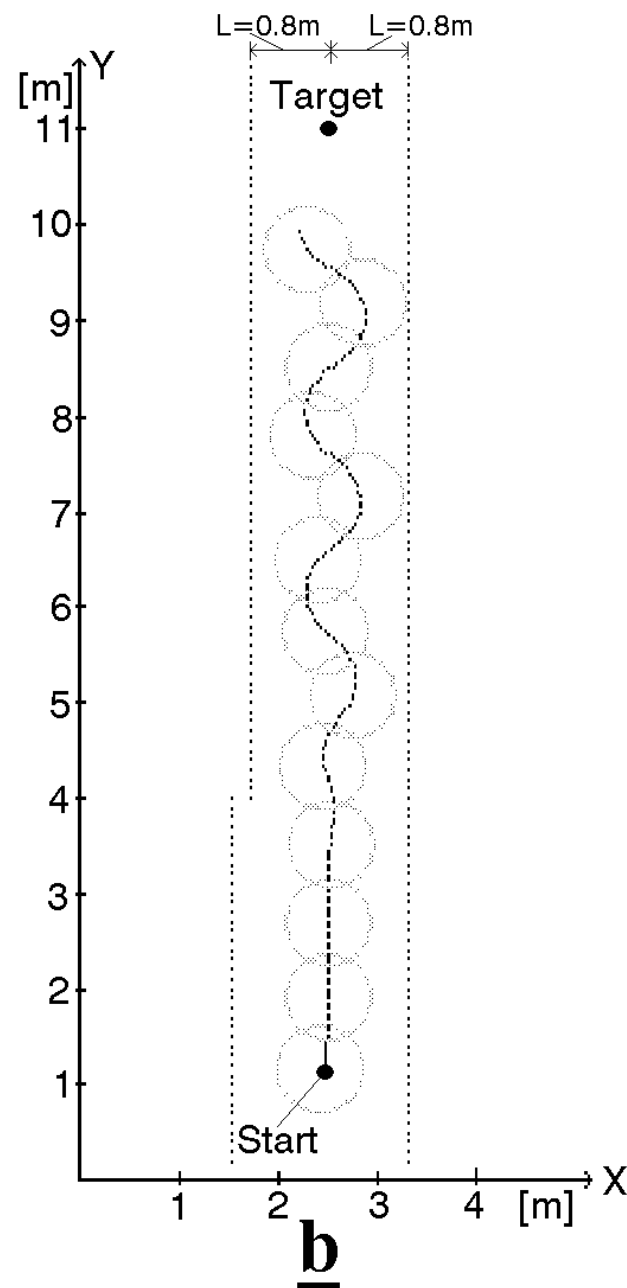


# Virtual force field: Borenstein & Koren

■ Problem:  
oscillations  
in narrow  
passages

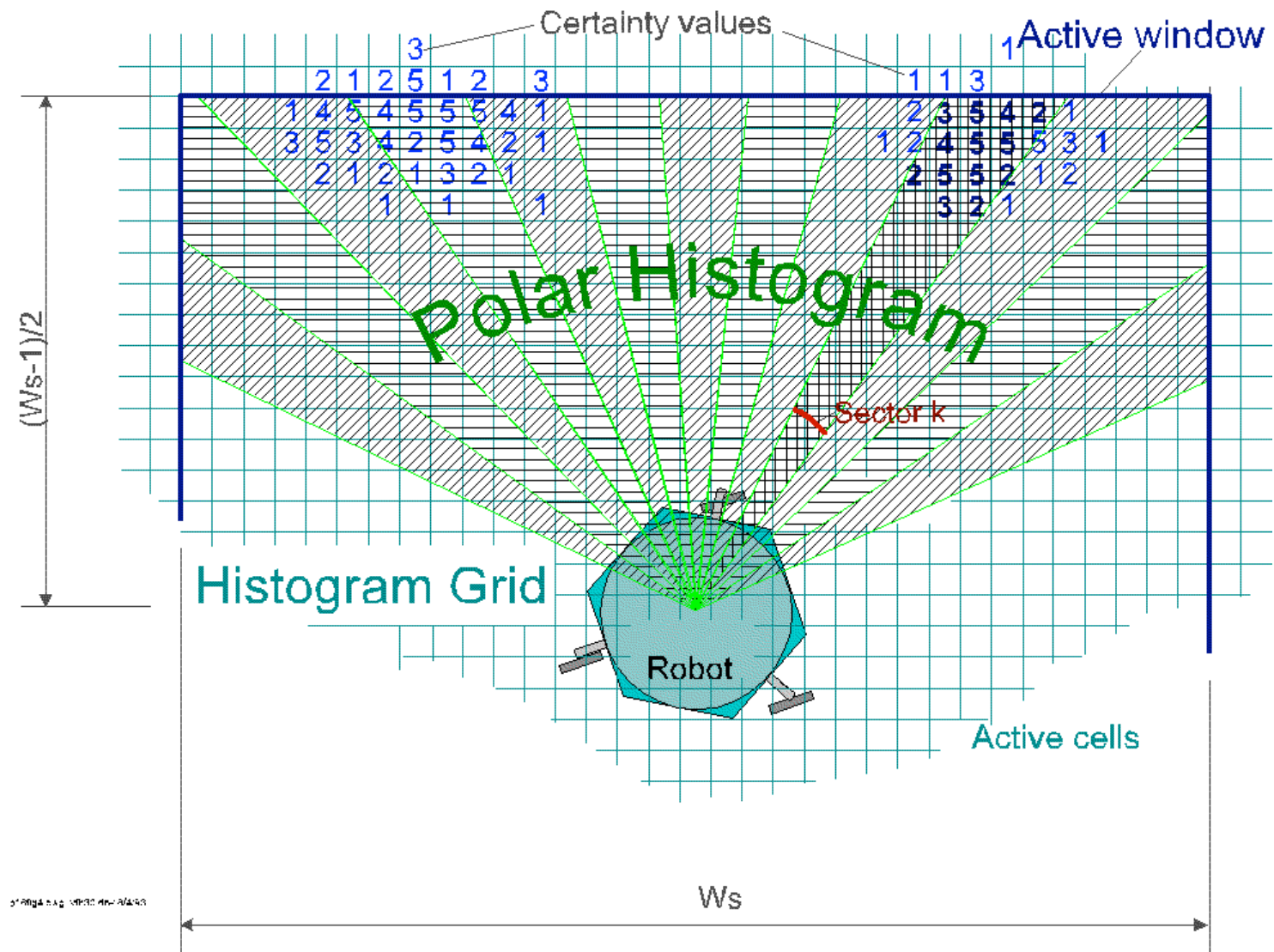


Stable motion in wide corridor  
 $V=0.8\text{m/s}$



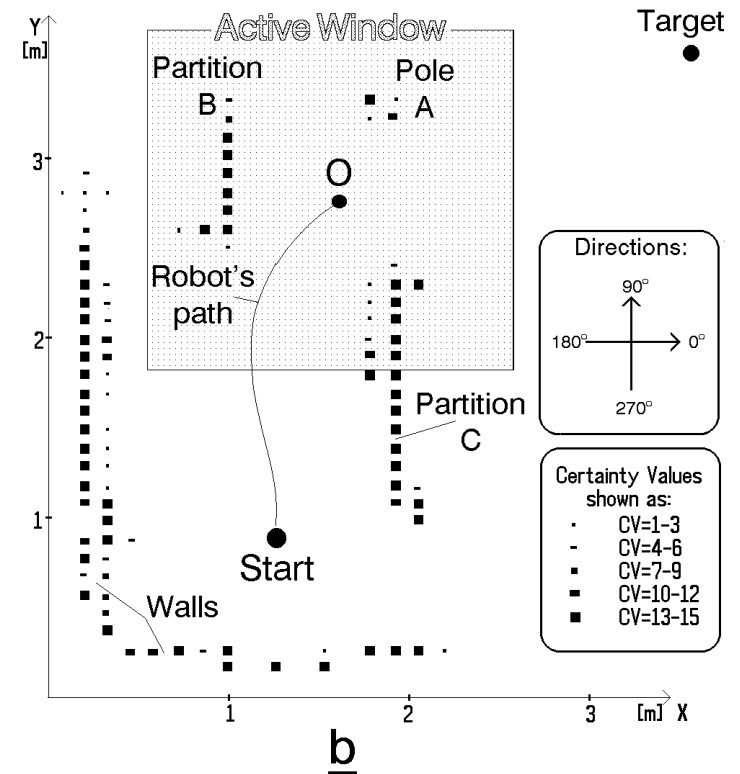
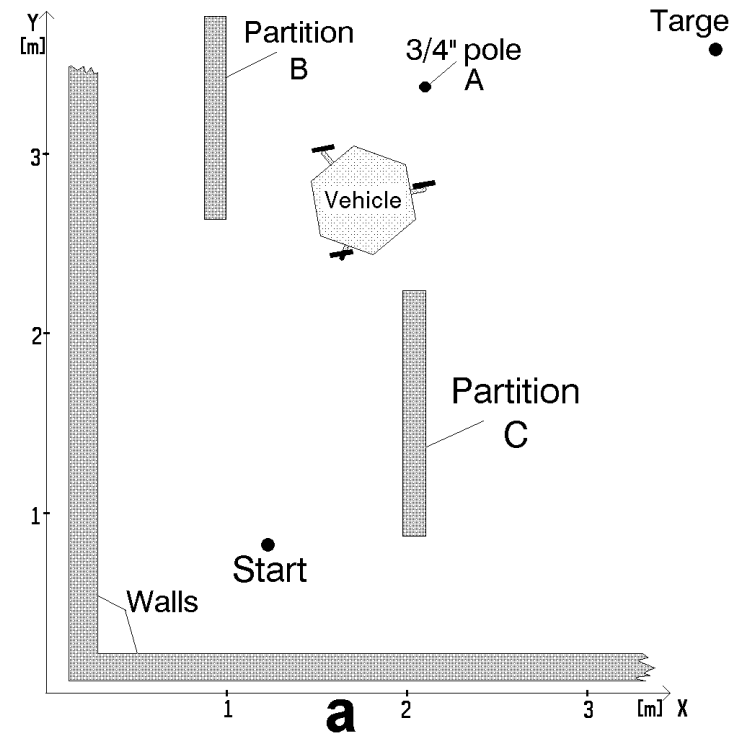
Unstable motion in narrow  
corridor.  $V=0.8\text{m/sec.}$

- transform active window in world grid into polar histogram



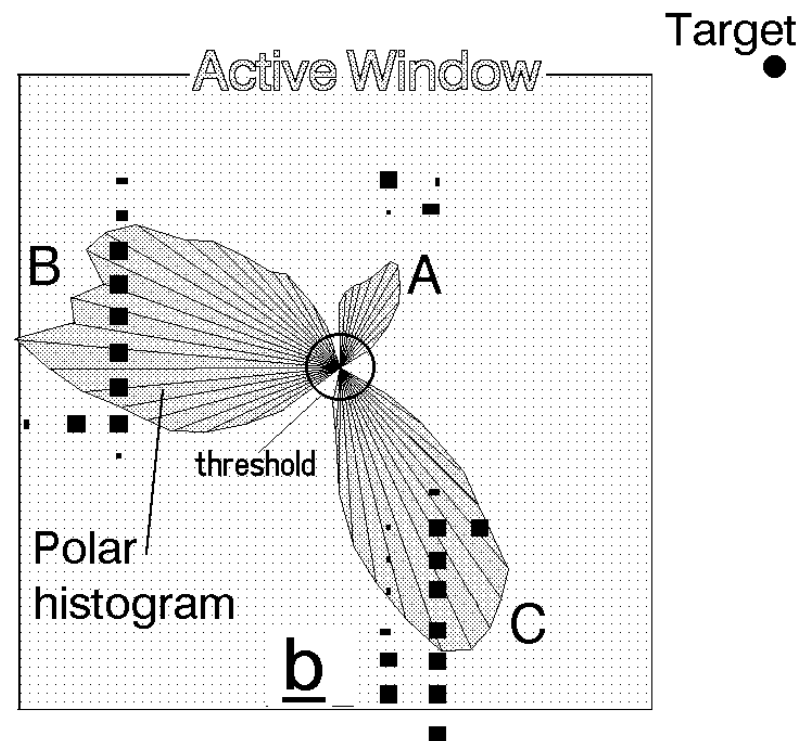
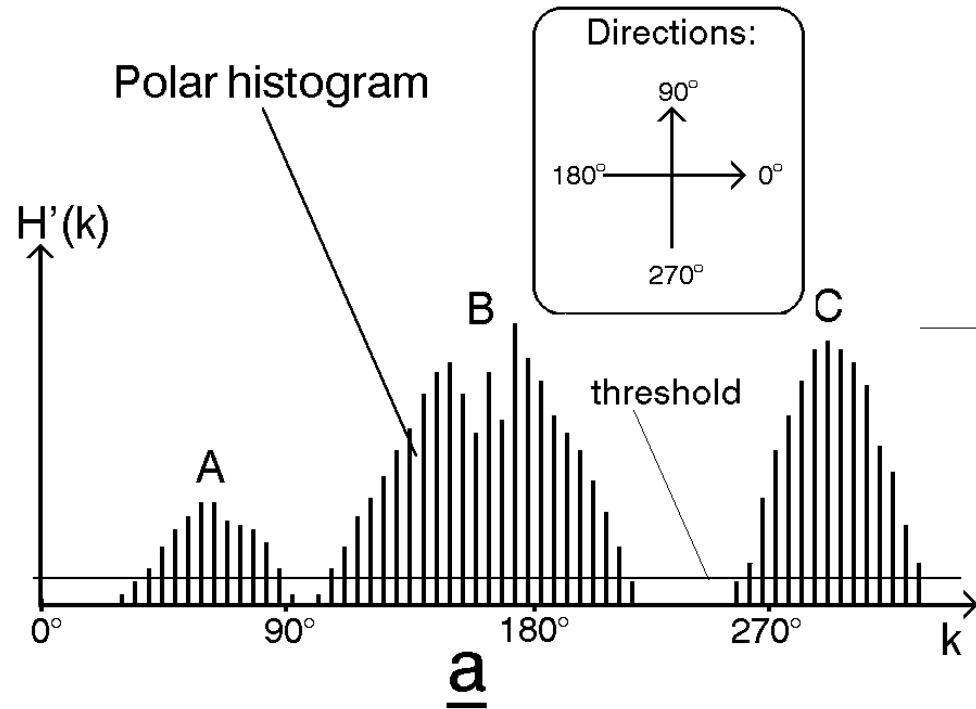
# Vector field histogram: Borenstein & Koren

■ lab set-up



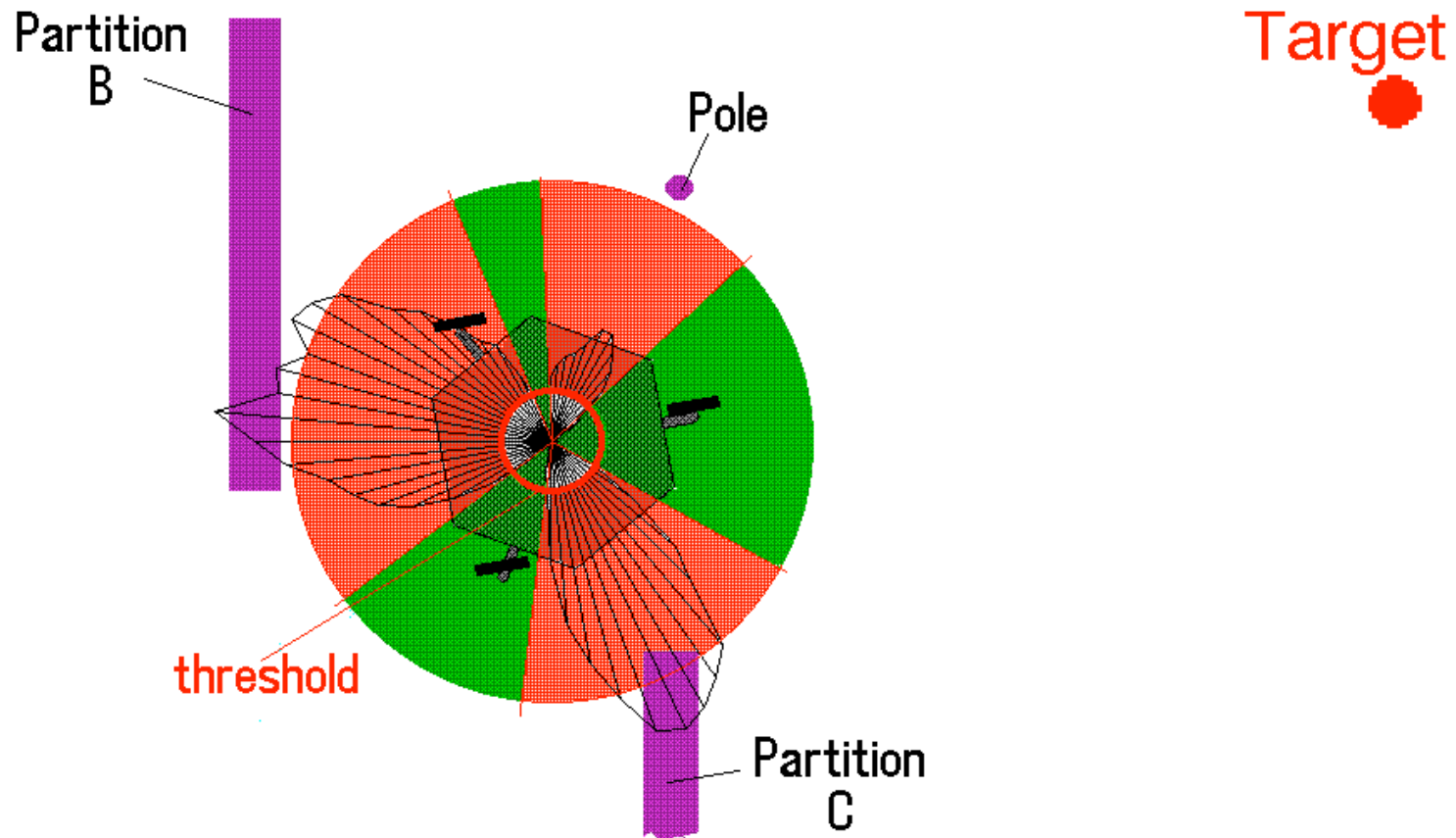
# Vector field histogram: Borenstein & Koren

- local polar histogram provides “free” directions

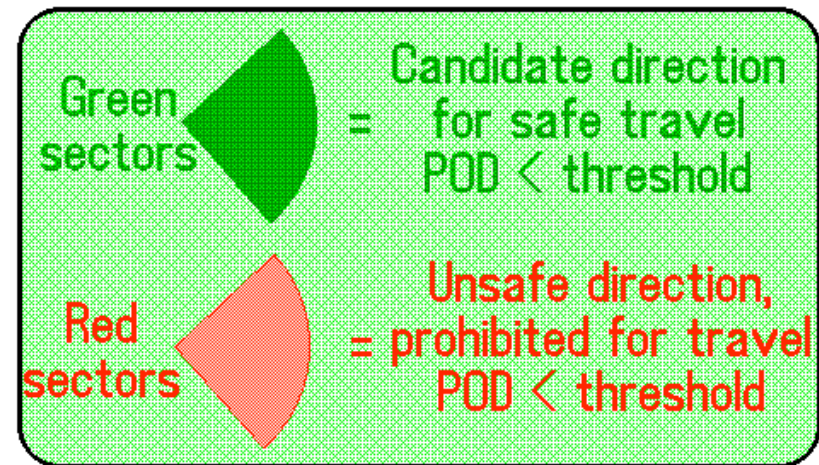


# Vector field histogram: Borenstein & Koren

■ Select safe direction algorithmically

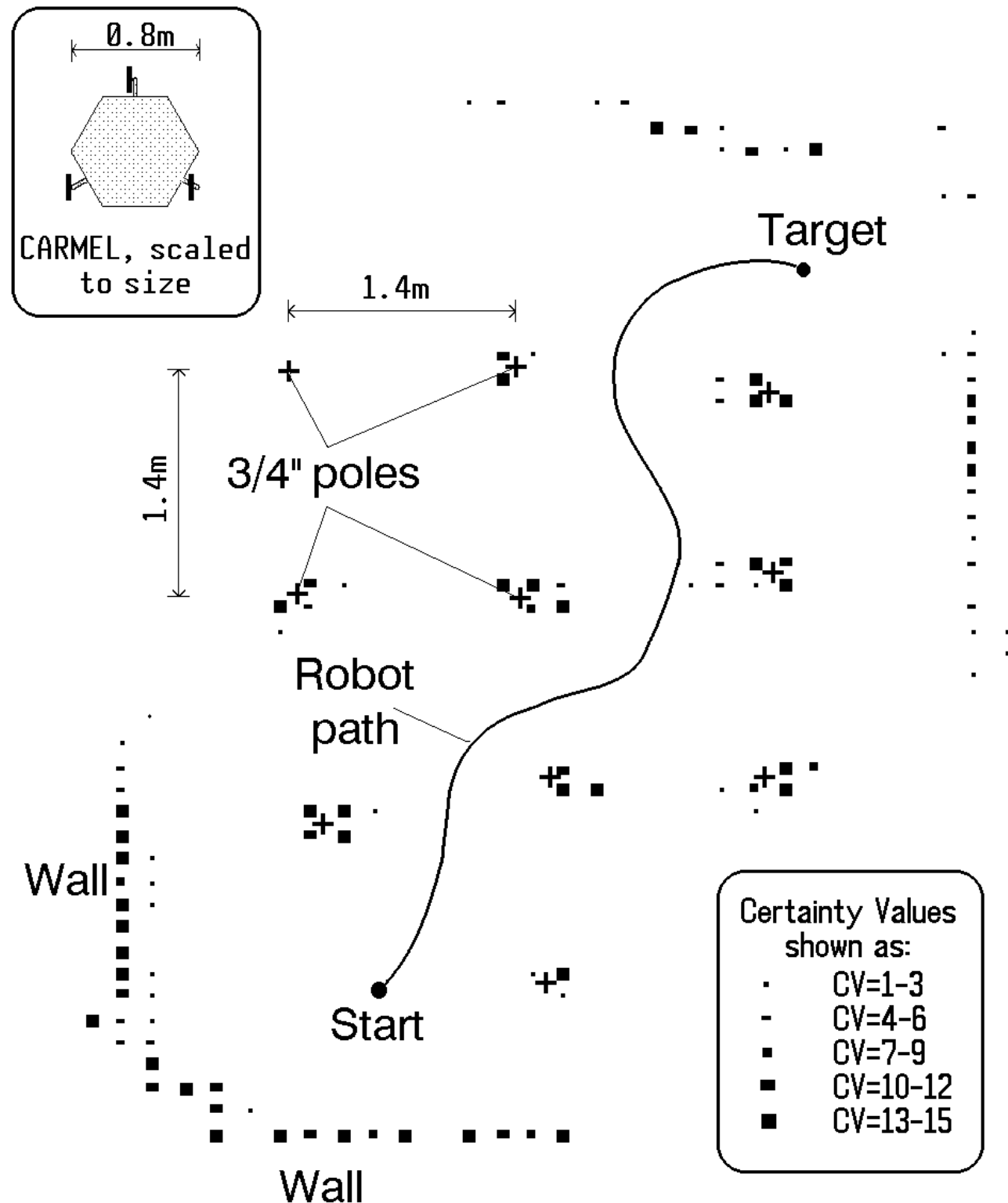


Finding candidate  
directions for safe travel



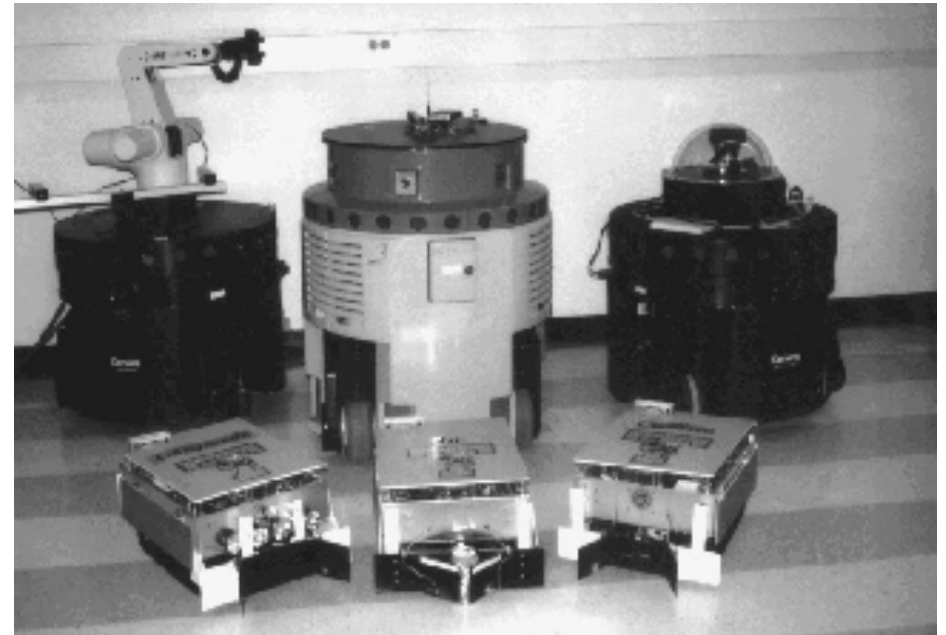
# Vector field histogram: Borenstein & Koren

■ works



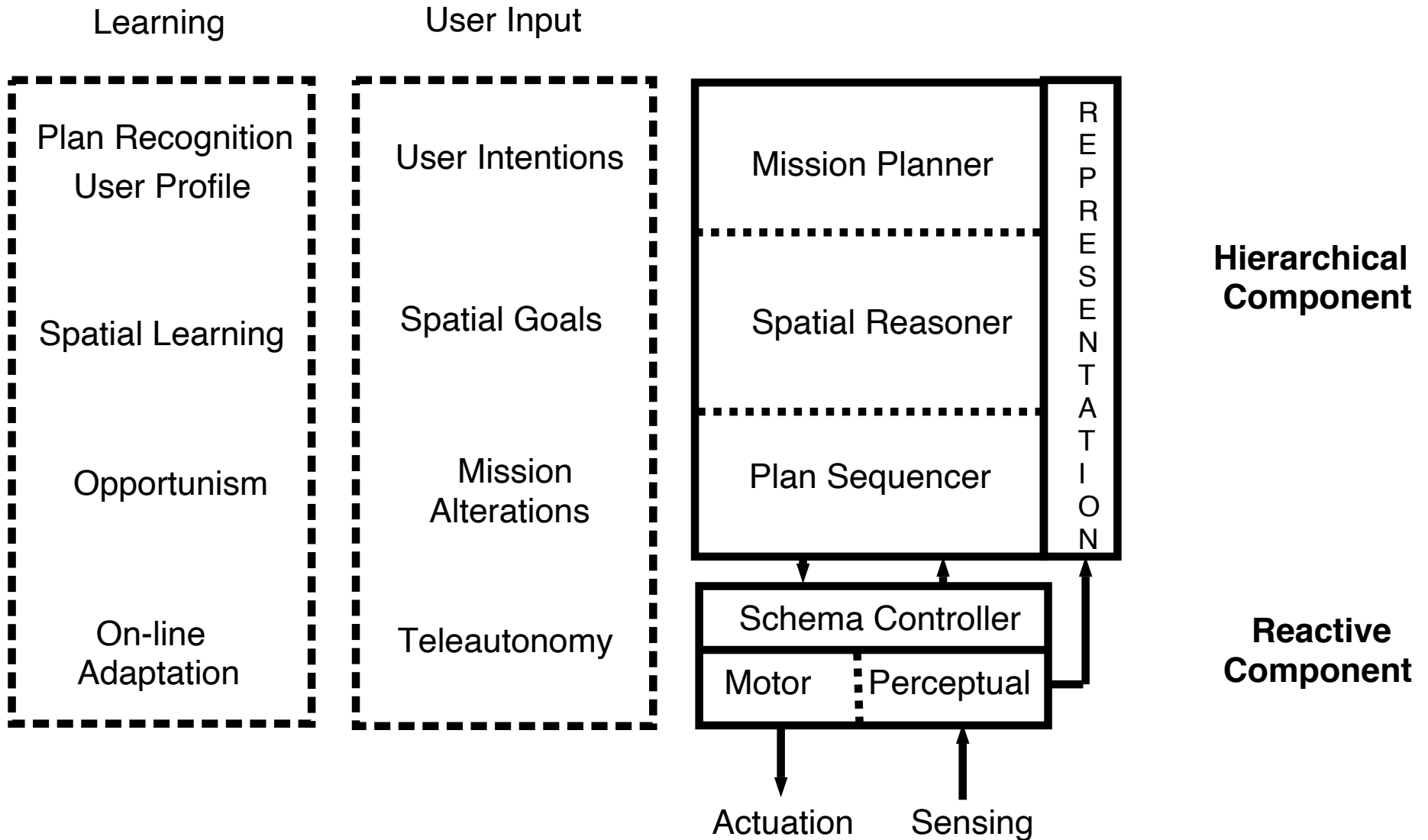
# Potential fields as reactive planners

- use potential field to plan locally based on low-level sensory information (reactive)
- different “behaviors” generated by different vector-fields (“schema”, slight generalization of potential fields)
- organize the different behaviors in an architecture

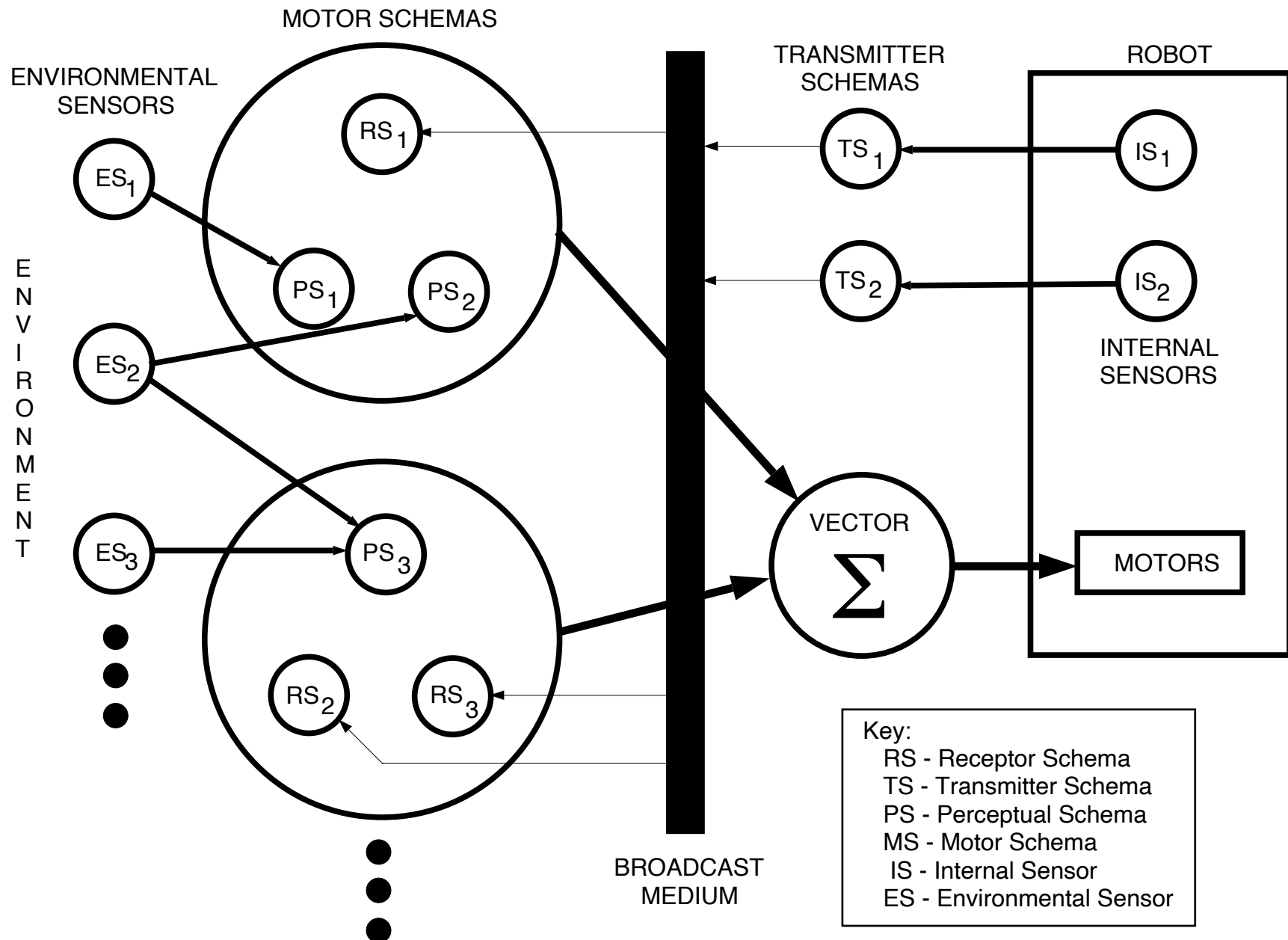


[Arkin, Blach: AuRA 1997]

# Architecture



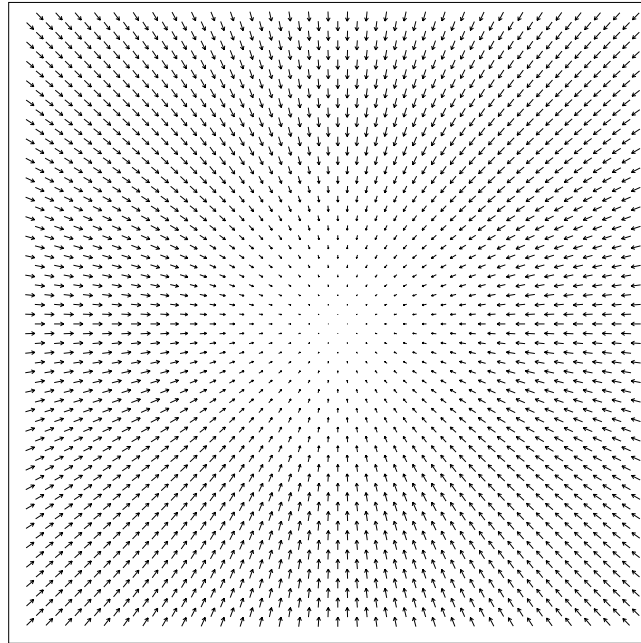
# The reactive component



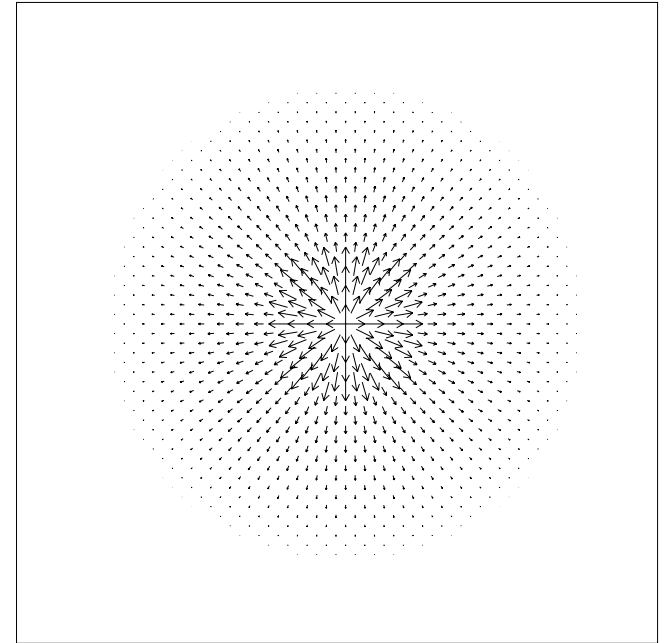
# Motor schemata

- **Move-ahead:** move in a particular compass direction.
- **Move-to-goal** (both ballistic and guarded): move towards a discrete stimulus.
- **Stay-on-path:** move towards the center of a discernible pathway, e.g., a hall or road.
- **Avoid-static-obstacle:** move away from non-threatening obstacles.
- **Dodge:** sidestep approaching ballistic objects.
- **Escape:** Evade intelligent predators.
- **Noise:** move in a random direction for a fixed amount of time. (persistence)
- **Avoid-past:** move away from recently visited areas.
- **Probe:** move towards an open area.
- **Dock:** move in a spiral trajectory towards a particular surface.
- **Teleautonomy** - introduce a human operator at the same level as other behaviors.

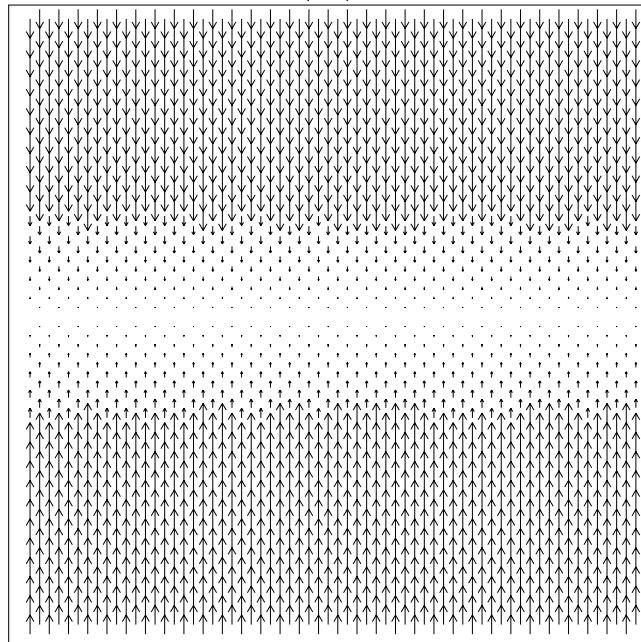
# Vector-fields for different behaviors (schemata)



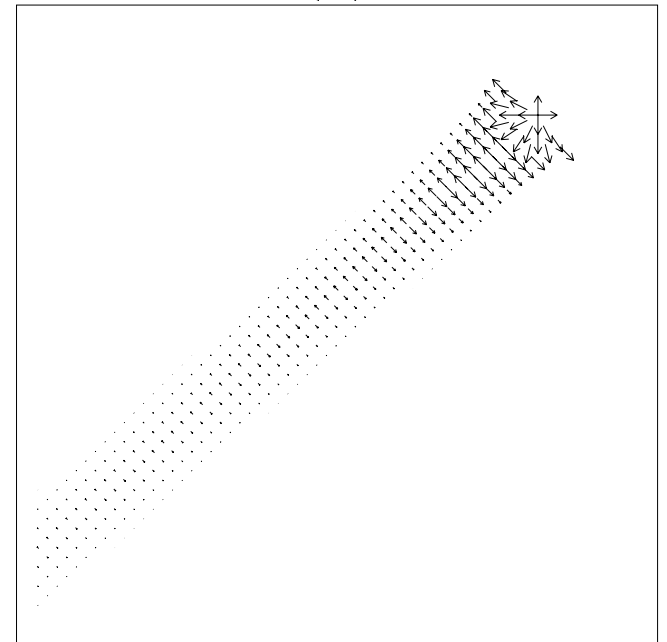
(A)



(B)

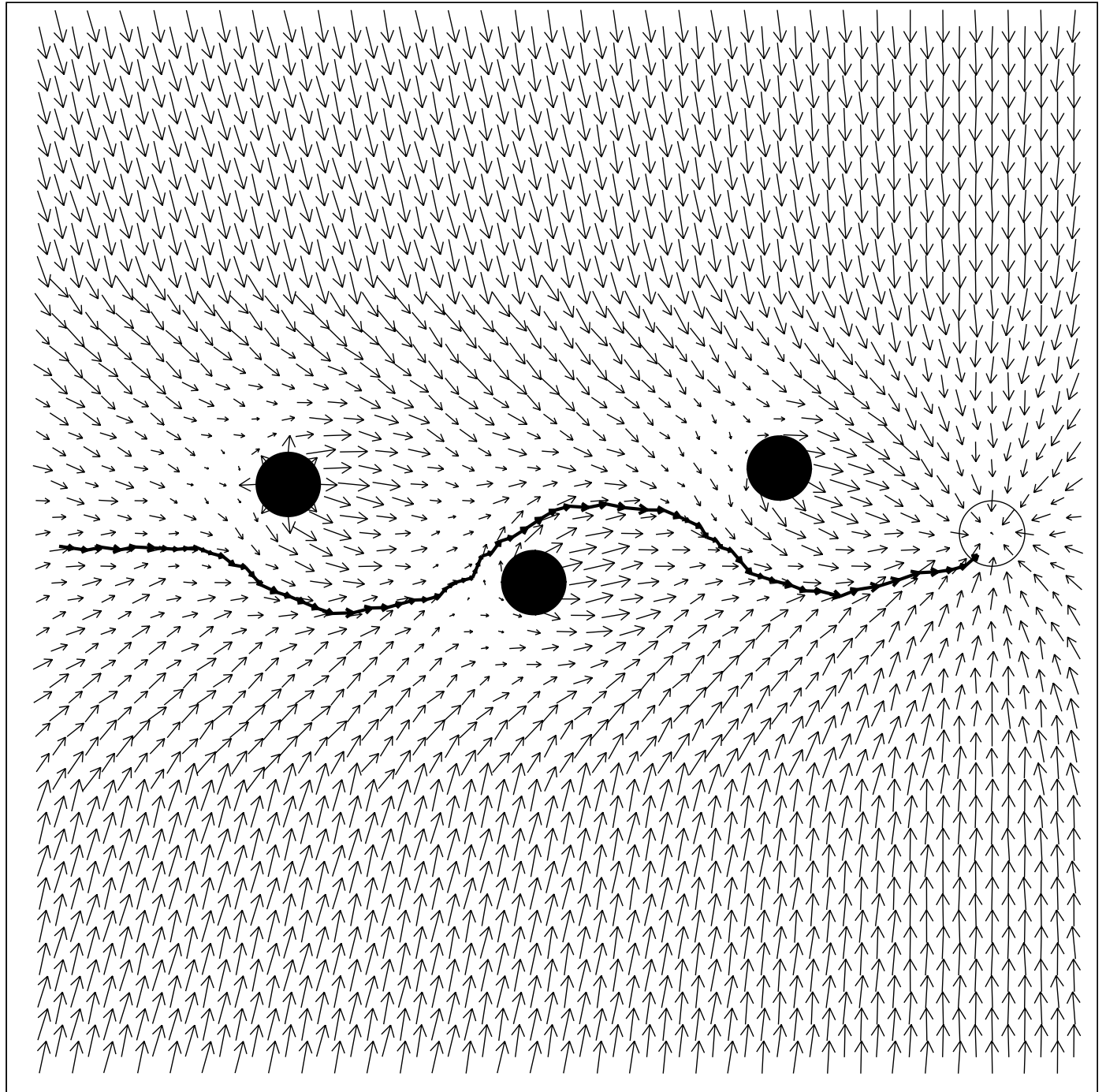


(C)

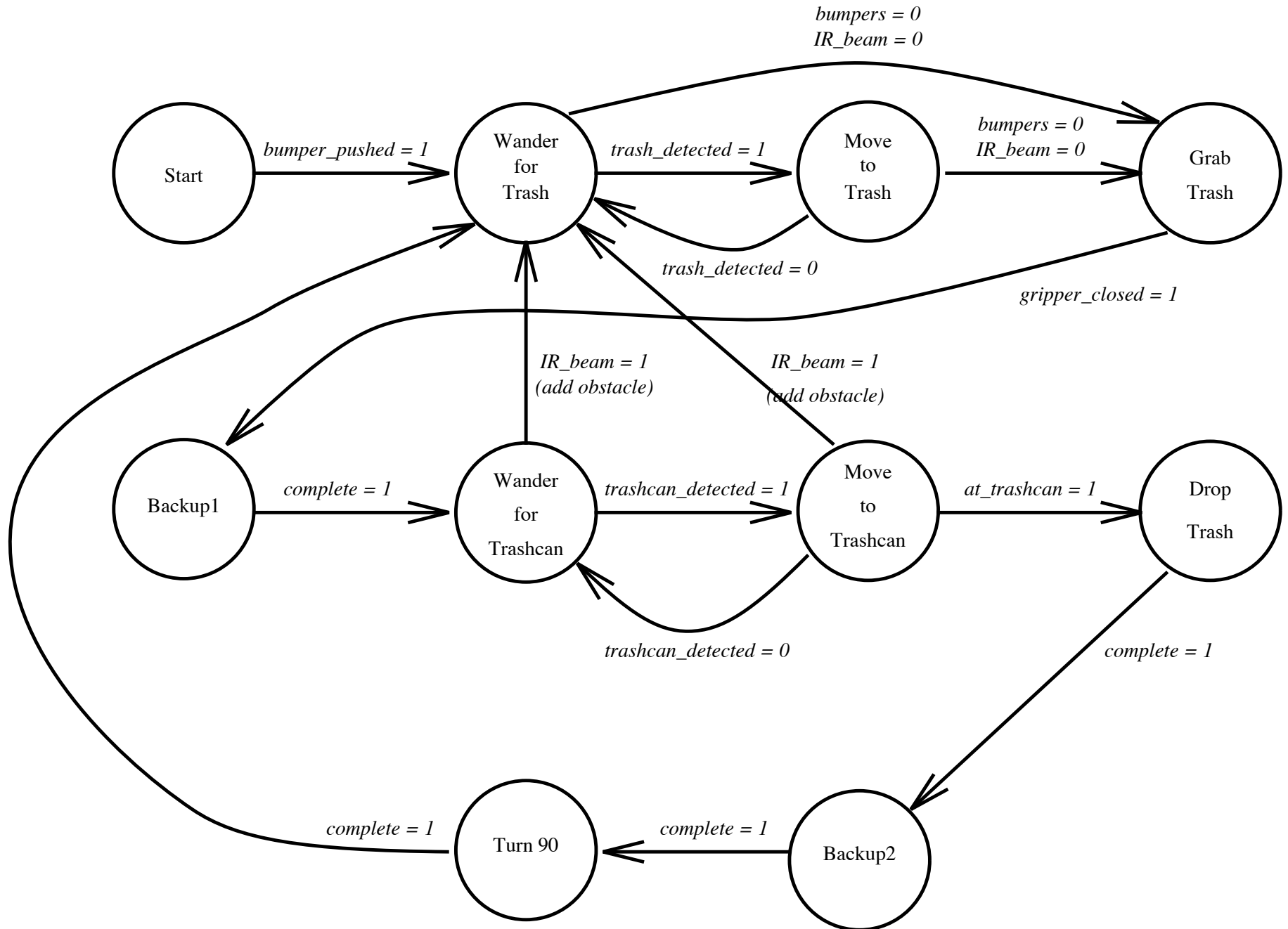


(D)

Superposing  
potential  
fields to  
combine  
behaviors

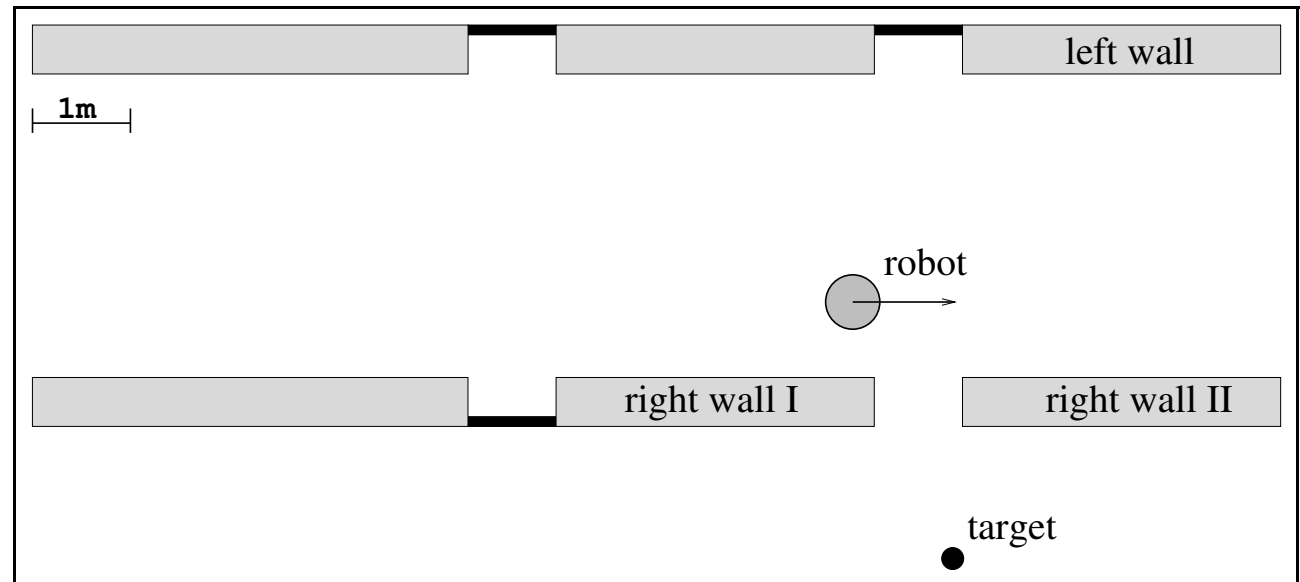


# Behavior-based sequence planner



# Dynamic window approach

- take dynamic constraints of vehicle into account (maximal decelerations/accelerations)... to drive fast



[Fox, Burghard, Thrun, 1996]

# Dynamic window approach

- discretize motor control space: linear and angular velocity
- => search space: circular trajectories of  $v$ ,  $\omega$

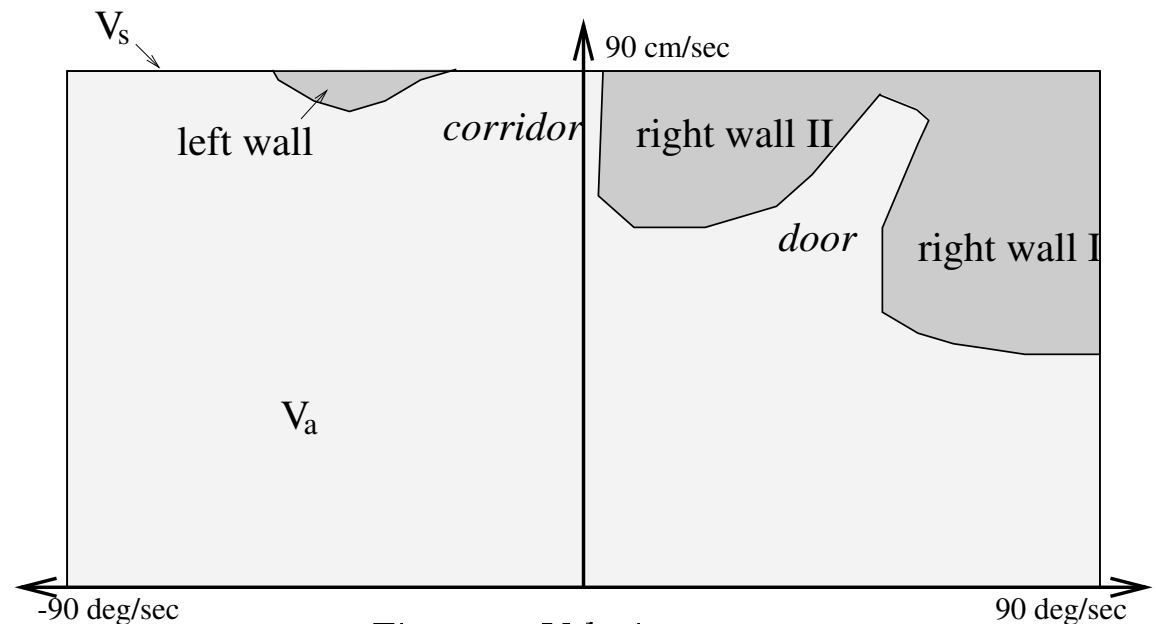


Figure 4. Velocity space

# Dynamic window approach

1. **Search space:** The search space of the possible velocities is reduced in three steps:
  - (a) **Circular trajectories:** The dynamic window approach considers only circular trajectories (curvatures) uniquely determined by pairs  $(v, \omega)$  of translational and rotational velocities. This results in a two-dimensional velocity search space.
  - (b) **Admissible velocities:** The restriction to admissible velocities ensures that only safe trajectories are considered. A pair  $(v, \omega)$  is considered admissible, if the robot is able to stop before it reaches the closest obstacle on the corresponding curvature.
  - (c) **Dynamic window:** The dynamic window restricts the admissible velocities to those that can be reached within a short time interval given the limited accelerations of the robot.

# Dynamic window approach

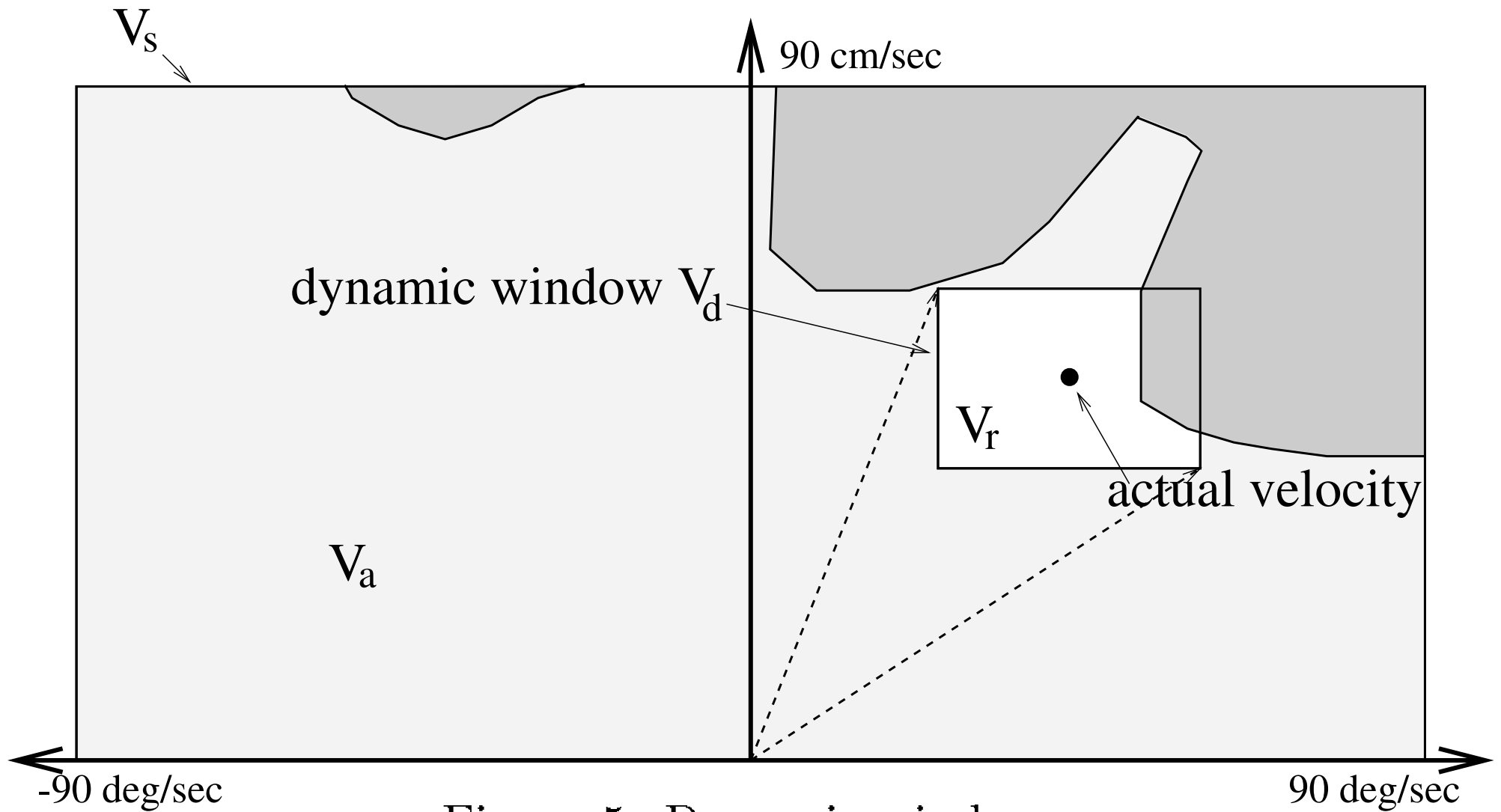


Figure 5. Dynamic window

# Dynamic window approach

2. **Optimization:** The objective function

$$G(v, \omega) = \sigma(\alpha \cdot \text{heading}(v, \omega) + \beta \cdot \text{dist}(v, \omega) + \gamma \cdot \text{vel}(v, \omega)) \quad (13)$$

is maximized. With respect to the current position and orientation of the robot this function trades off the following aspects:

- (a) **Target heading:** *heading* is a measure of progress towards the goal location. It is maximal if the robot moves directly towards the target.
- (b) **Clearance:** *dist* is the distance to the closest obstacle on the trajectory. The smaller the distance to an obstacle the higher is the robot's desire to move around it.
- (c) **Velocity:** *vel* is the forward velocity of the robot and supports fast movements.

The function  $\sigma$  smoothes the weighted sum of the three components and results in more side-clearance from obstacles.

# Dynamic window approach

## ■ target cost function

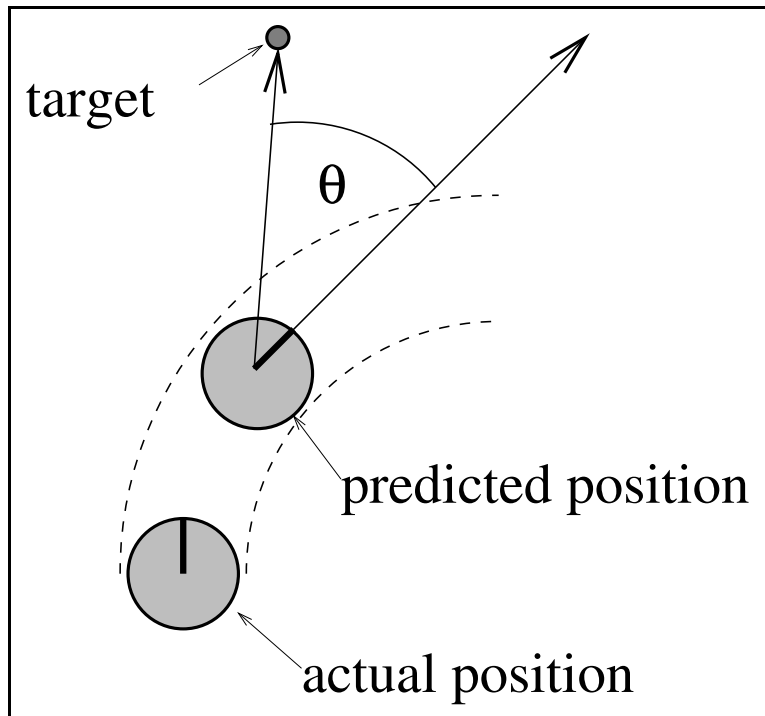


Figure 6. Angle  $\theta$  to the target

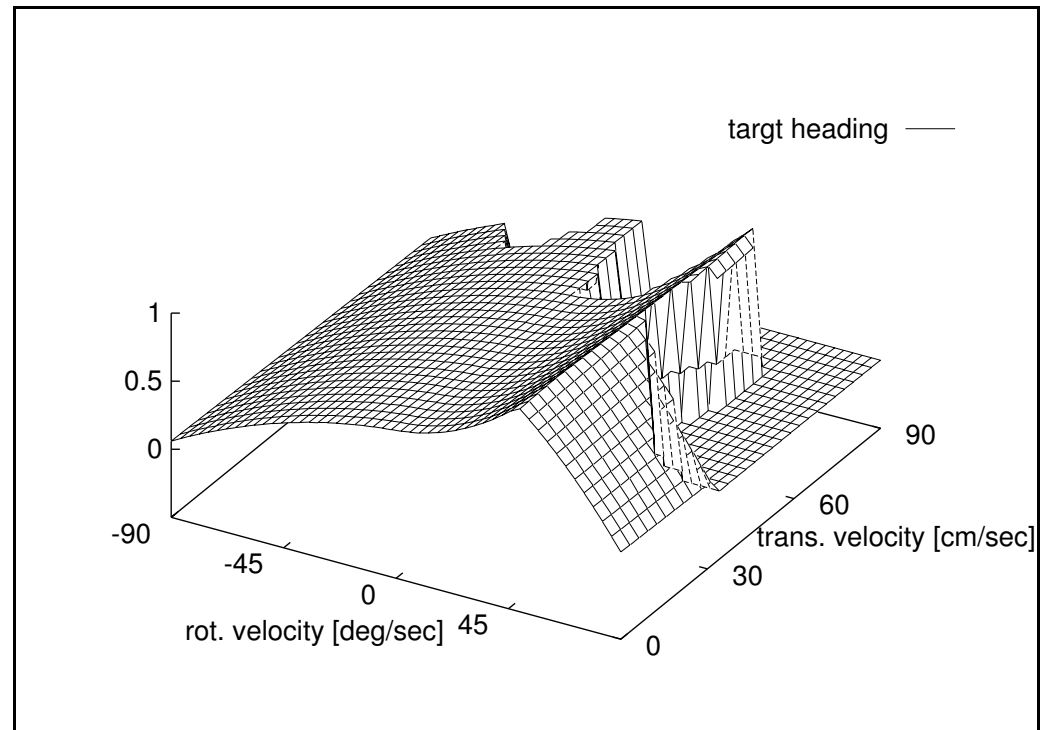


Figure 7. Evaluation of the target heading

# Dynamic window approach

## ■ clearance cost function

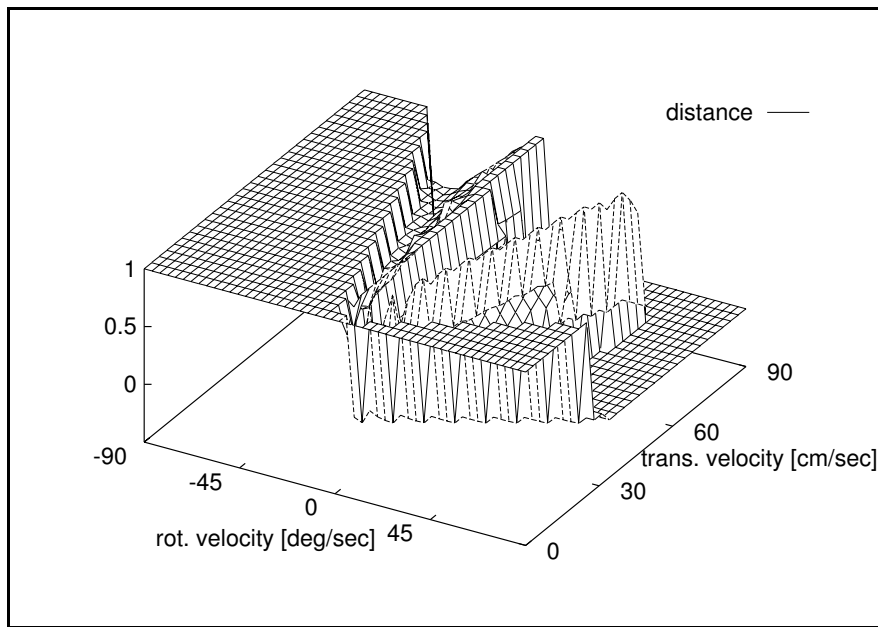


Figure 8. Evaluation of the distances

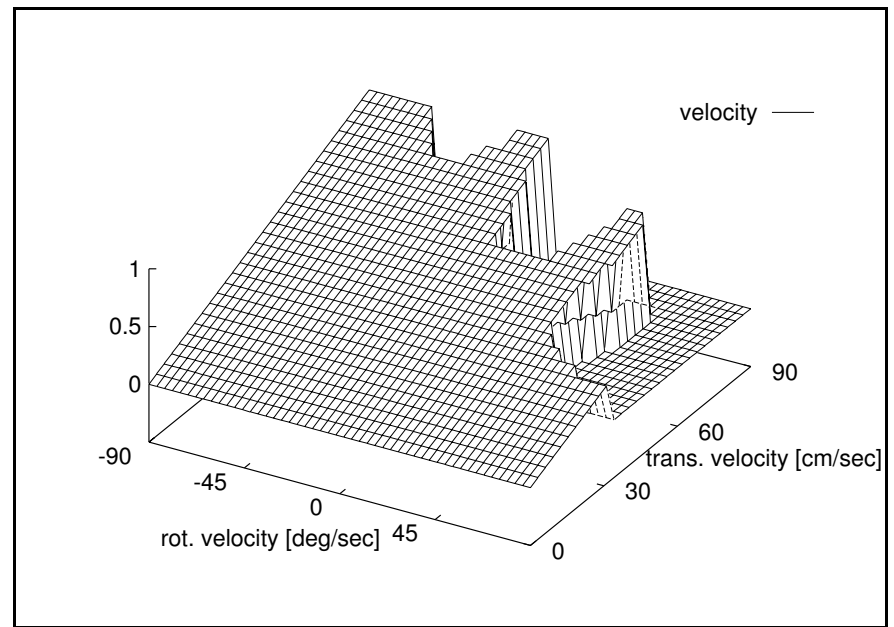


Figure 9. Evaluation of the velocities

# Dynamic window approach

## ■ smoothing the cost functions

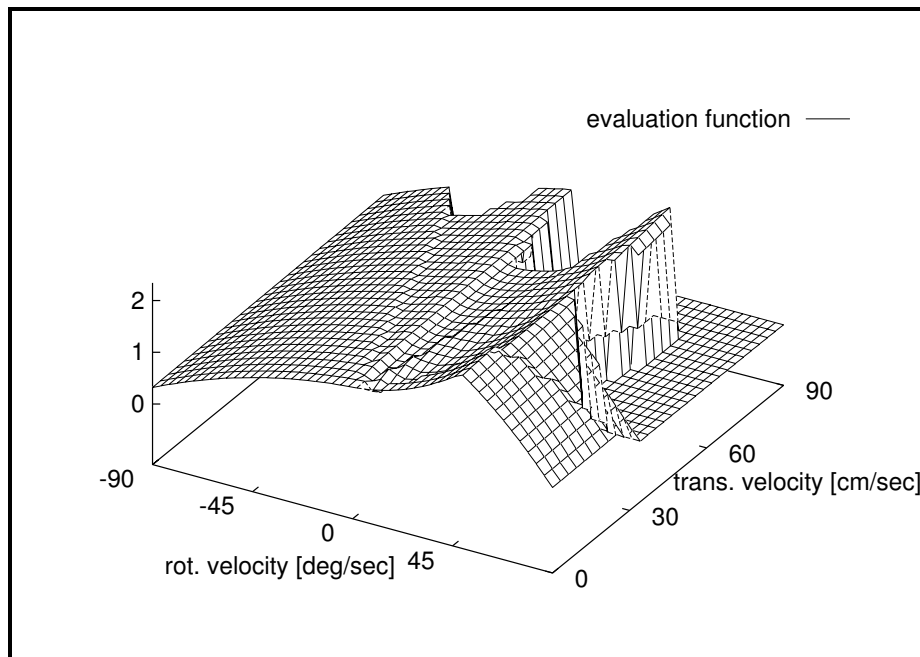


Figure 10. Combined evaluation function

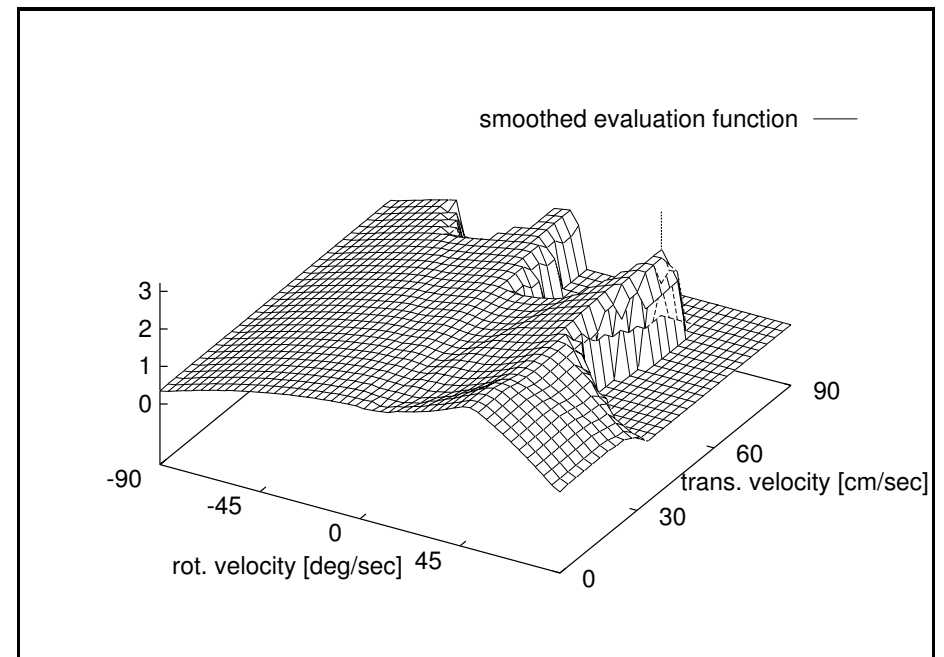


Figure 11. Objective function

# Dynamic window approach

- two samples of actual velocities

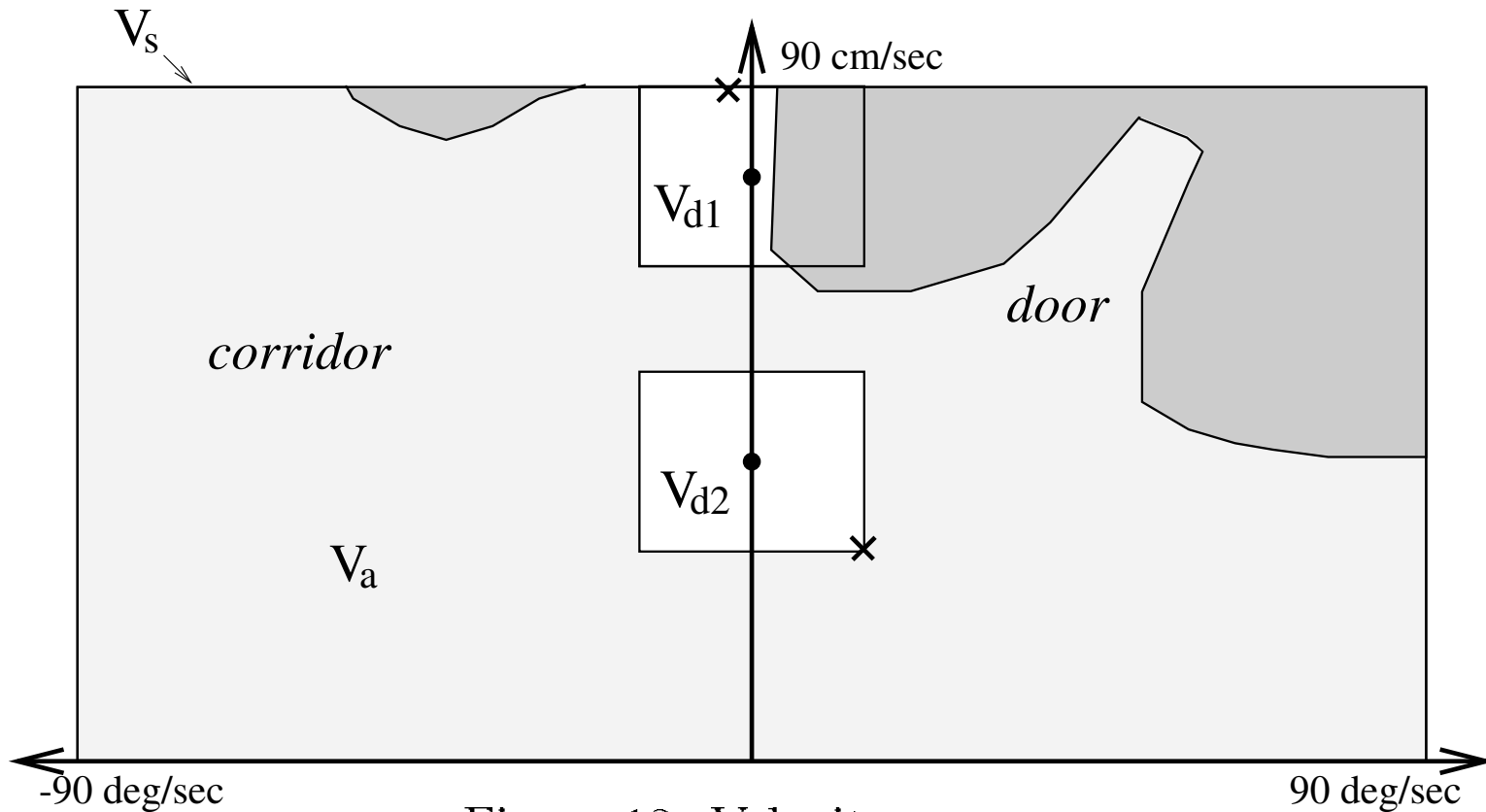


Figure 12. Velocity space

# Dynamic window approach

■ cost function for the action velocities

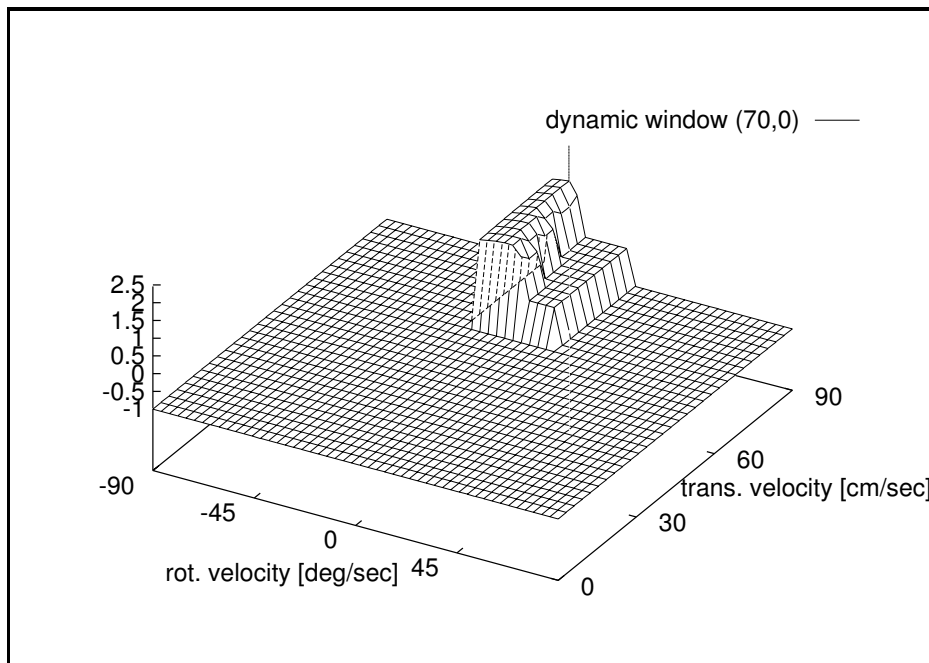


Figure 13. Objective function for actual velocity (75,0)

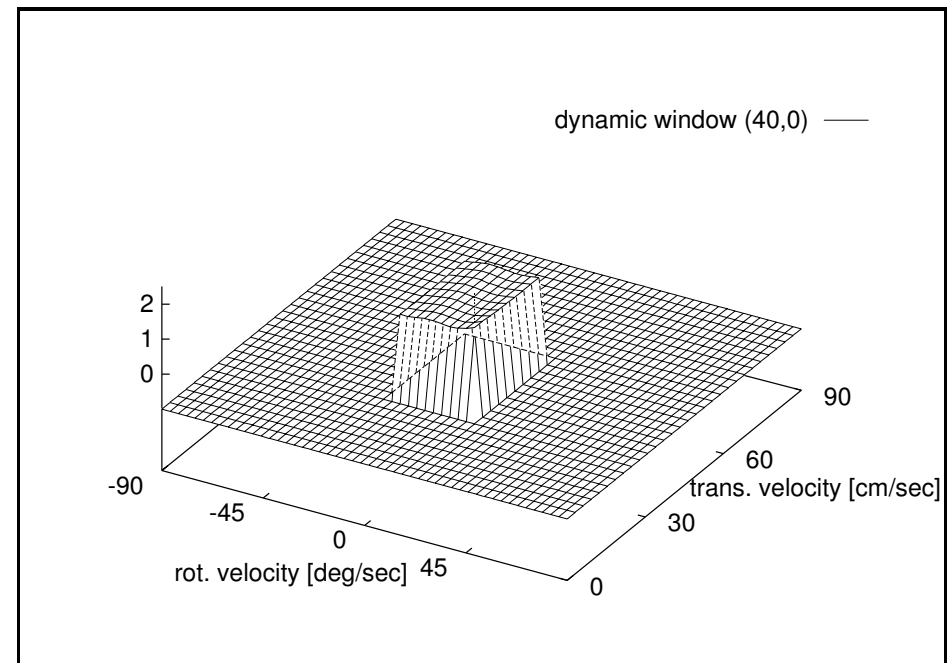


Figure 14. Objective function for actual velocity (40,0)

# Dynamic window approach

- example RHINO
- used Borenstein Koren approach to smooth and accumulate sonar distance data

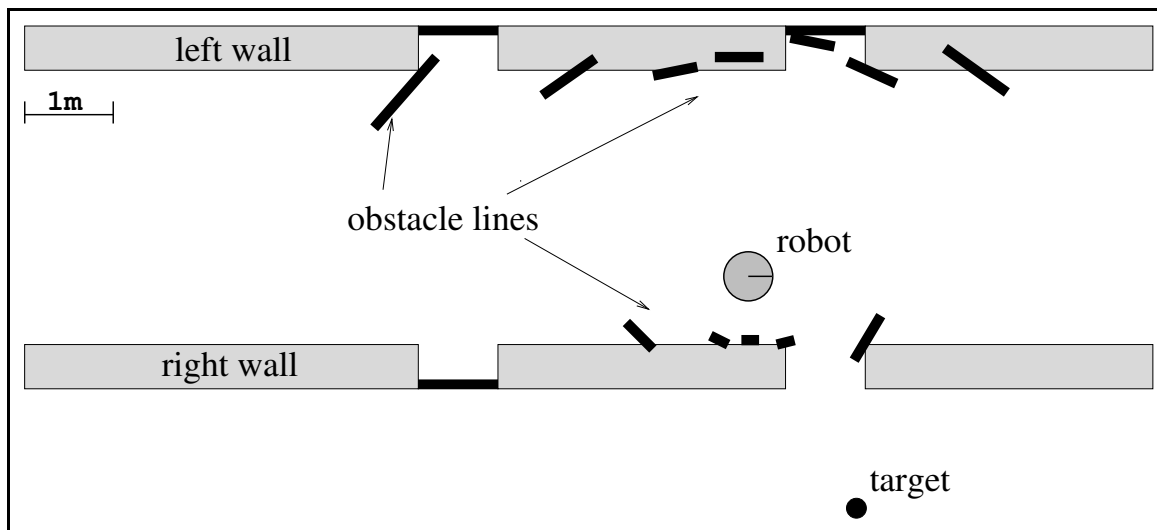
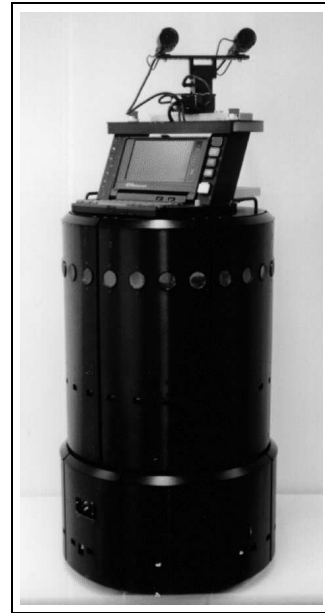


Figure 18. Example environment with obstacle lines and target point

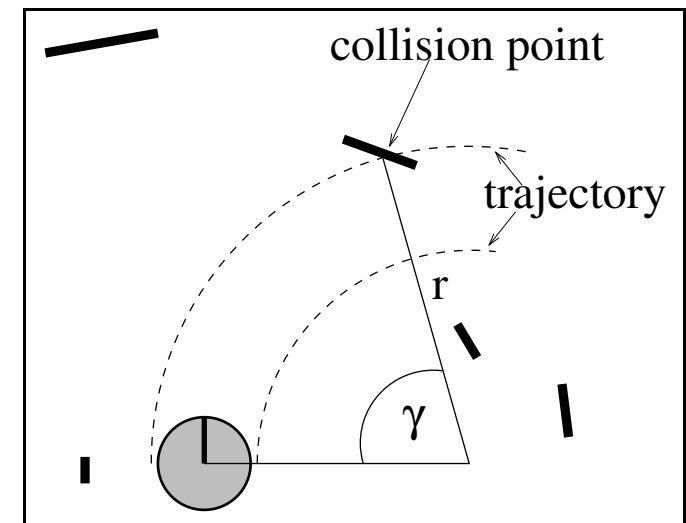


Figure 19. Determination of the distance

# Dynamic window approach

■ data

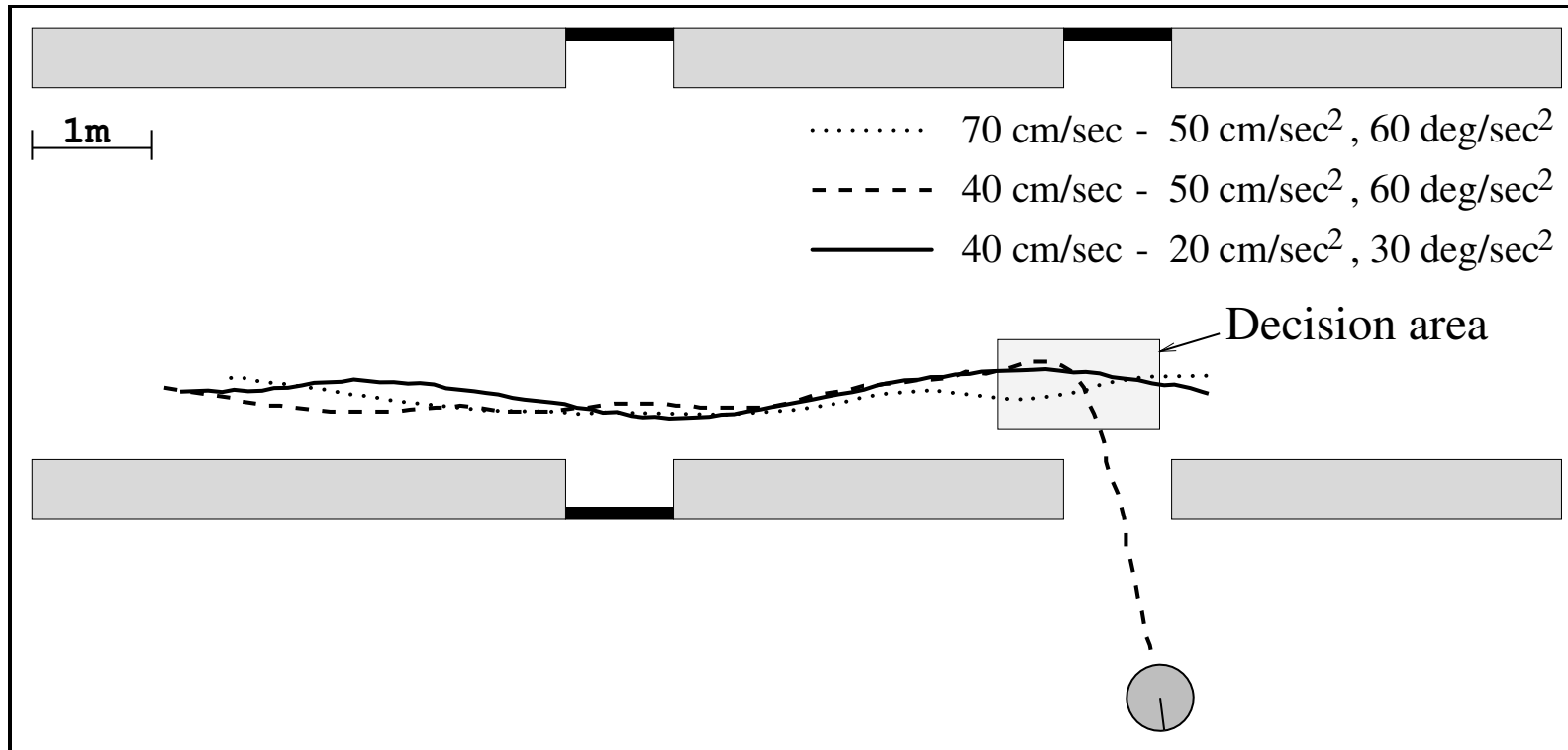


Figure 20. Trajectories chosen for different dynamic parameters

# Dynamic window approach

■ data

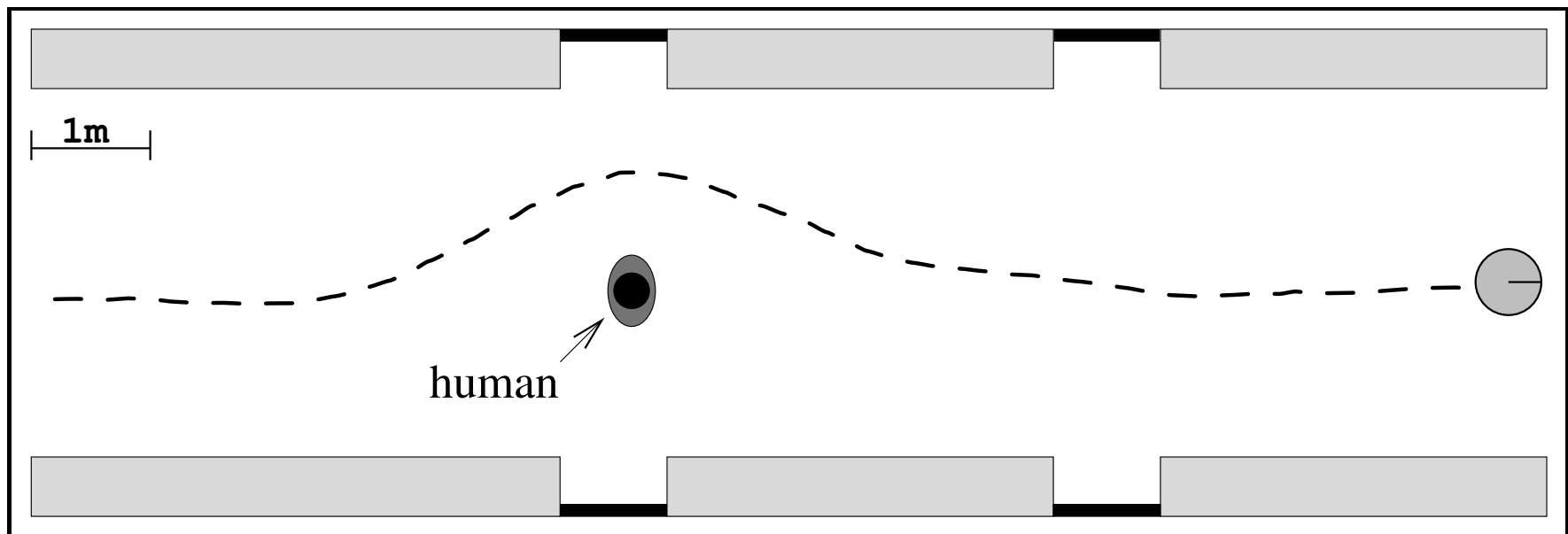


Figure 21. Trajectory through corridor

# Dynamic window approach

■ data

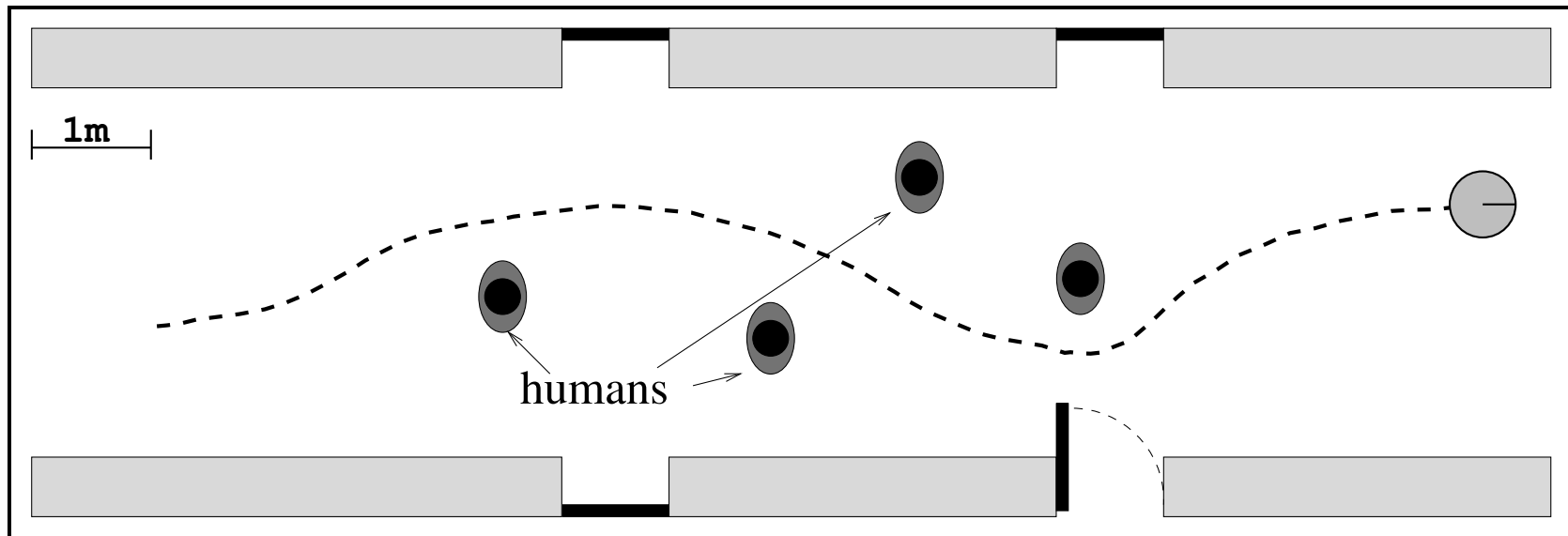


Figure 22. Trajectory through cluttered corridor

# Summary

- powerful approaches exist for motion planning
- the best/exact approaches make strong demands on world representations and computation
- heuristic “reactive” approaches are state of the art (often combined in hybrid architectures with deliberative planning)
- the attractor dynamics approach is competitive as a reactive approach

# Outlook

- deliberative planning...
  - moving beyond the vehicle navigation problem
  - planning sequences of actions to achieve goals
  - searching spaces, often represented as graphs
  - ... a huge field...
- not very satisfactorily included in neurally based approaches..