Master in Bionics Engineering
University of Pisa and Scuola Superiore Sant'Anna

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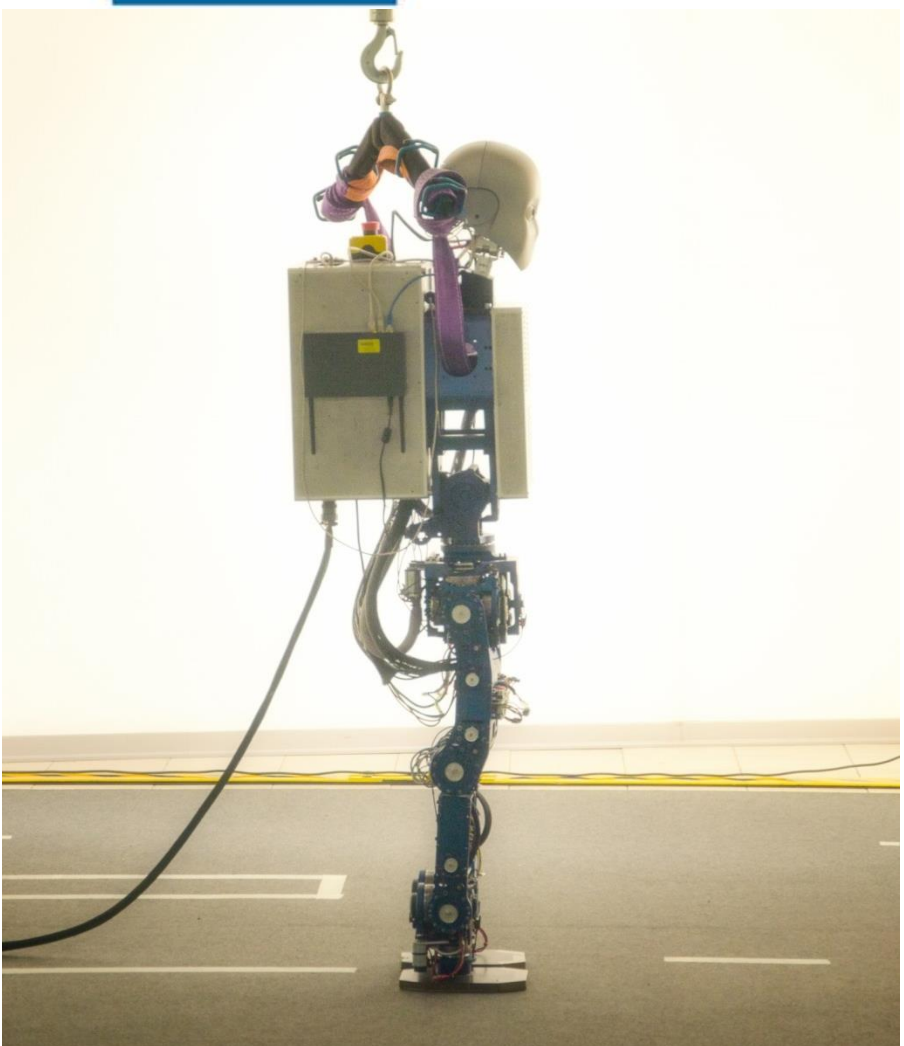

Biomimetic robot navigation

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M.O. Franz, H.A. Mallot, "Biomimetic robot navigation", *Robotics and Autonomous Systems*, 30, 2000

Summary of bioinspired approaches to robotics (in this course…)

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Robot vision

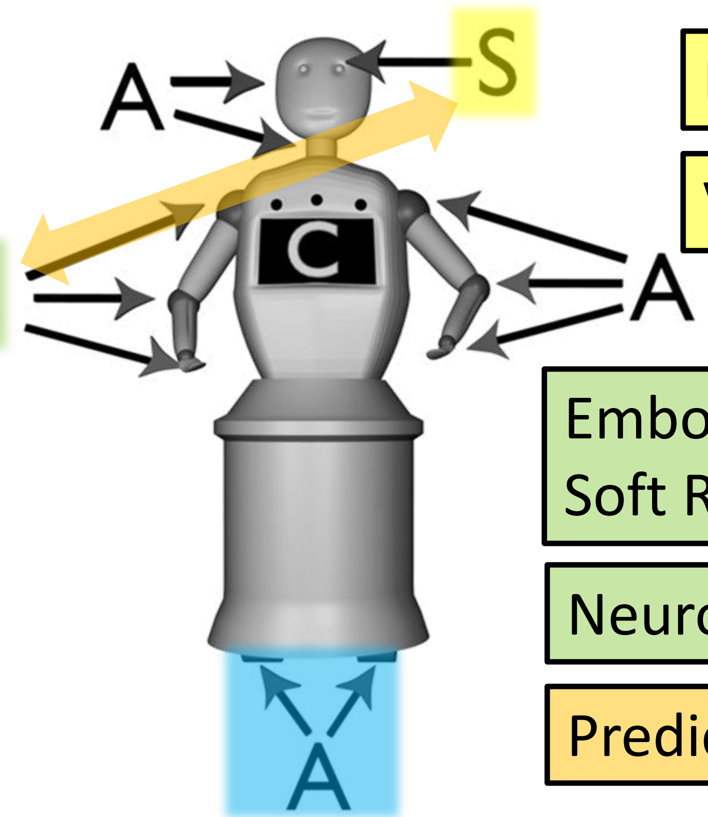
Robot sensors

Robot mechanics and kinematics

Robot control

Robot behaviour

Robot navigation



Bioinspired vision

Vestibular system

Embodied Intelligence, Soft Robotics

Neurocontrollers

Predictive behaviour

Bioinspired navigation, Soft locomotion

Fundamental problems of robot navigation

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To reach a final position from a starting position, given in geometric or sensory terms, avoiding obstacles

The classical questions to solve are:

- **Where am I?**
- **Where are the other objects around me?**
- **How can I reach a desired position?**

Robot navigation class

Bioinspired robot navigation

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To reach a final position from a starting position, given in geometric or sensory terms, avoiding obstacles

The classical questions to solve are:

- **Where am I?**
- **Where are the other objects around me?**
- **How can I reach a desired position?**

- **How do I reach the goal?**

Bioinspired robot navigation definition

Navigation is the process of determining and maintaining a course or trajectory to a goal location

Required capabilities:

1. Move in space
2. Determine whether or not the goal has been found

   => the sensory features that identify the goal have to be stored in some form of long-term memory

In contrast with the classical approach, it does not imply that the current location must be recognised, nor that a map-like representation must be used to find the goal

Bioinspired robot navigation definition

Navigation is the process of determining and maintaining a course or trajectory to a goal location

Since there is a goal in navigation, it is different from:

- Exploration
- Foraging
- Obstacle avoidance
- Body orientation
- Course stabilization

‘taxis’ is not always a navigation mechanisms

(taxis = active body orientation to a direction given by a stimulus)

Bioinspired robot navigation navigation hierarchy

Local navigation

(or tactics)

It requires:

- Recognition of only one location, i.e. the goal

Actions are based on current sensory information

No representation of objects or places outside of the sensory horizon

Way finding

It requires:

- Recognition of several places
- Representation of relations between places, even outside the sensory horizon

It relies on local navigation skills to move from one place to another, but it allows to find places that cannot be found by local navigation alone

No relation to scale

Bioinspired robot navigation - navigation hierarchy

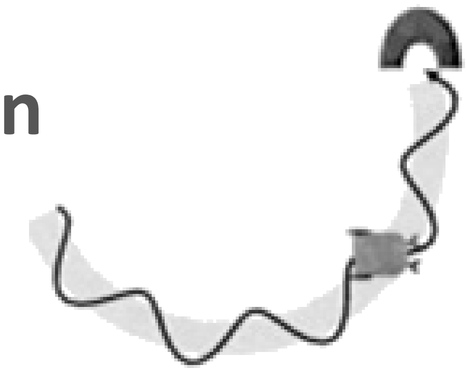
		Behavioural prerequisite	Navigation competence
Local navigation	Search	Goal recognition	Finding the goal without active goal orientation
	Direction-following	Align course with local direction	Finding the goal from one direction
	Aiming	Keep goal in front	Finding a salient goal from a catchment area
	Guidance	Attain spatial relation to the surrounding objects	Finding a goal defined by its relation to the surroundings
Way finding	Recognition-triggered response	Association sensory pattern–action	Following fixed routes
	Topological navigation	Route integration, route planning	Flexible concatenation of route segments
	Survey navigation	Embedding into a common reference frame	Finding paths over novel terrain

Local navigation – search

- No active orientation towards a goal
- The goal is found by chance
- It requires basic competences of:
  - Locomotion
  - Goal detection
- No spatial representation
- Large amount of time needed to reach the goal

=> It can be used as a backup strategy

Local navigation – direction following and path integration



Direction following

- It requires competences of:
  - Aligning its course with locally-available direction to find the goal
- No need to perceive the goal
- Direction can be given by:
  - *Allothetic* sources: based on external references
  - *Idiothetic* sources: based on internal references
- It needs to move along a trail defined by the direction – if the trail is missed, the goal is not reached

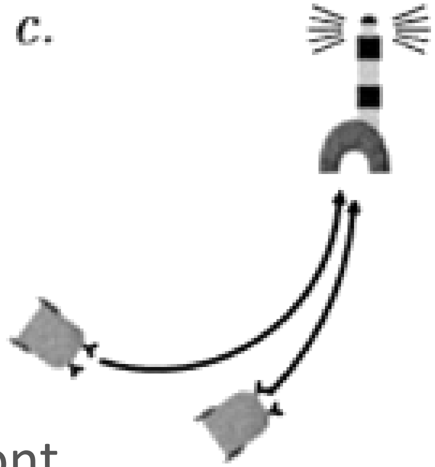
Ex: ship navigating by compass

Path integration

- It requires to know the distance from the goal, too

=> odometry

Local navigation – aiming

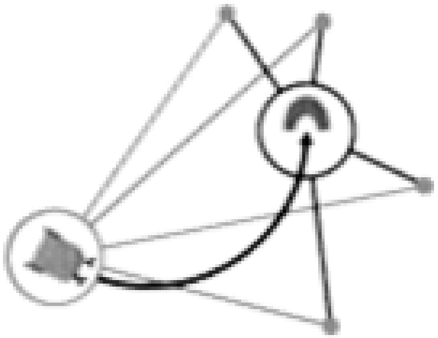


- It requires competences of:
  - Orienting its body axis such that the goal is in front
  - Perceiving the goal at all times – ‘catchment area’
  - The goal must be associated to some salient cue

Ex: beacons

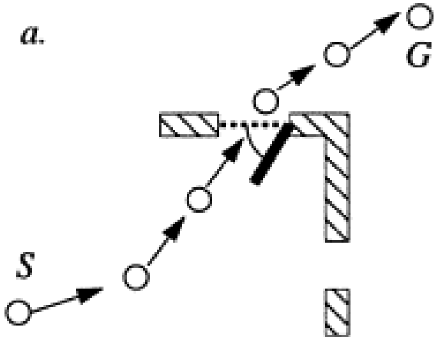
- Differently from direction following, the goal can be approached by any direction, with no risk for cumulative error

Local navigation – guidance



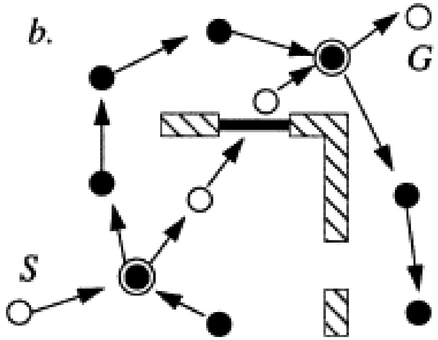
- Guided by the spatial configuration of the surrounding objects
- It requires competences of:
    - Maintaining a certain egocentric relationship with respect to a particular landmark or object
    - Spatial information in terms of relations between the current location, the goal, the currently perceiptible environment

Way finding – recognition-triggered response



- Connecting two locations by a local navigation method
- The recognition of a location triggers the activation of a local navigation method leading to the goal
- Formally denoted by a pair
  (starting location, local navigation method)
- It requires competences of:
  - Recognizing the goal
  - Recognizing the starting location – certain sensory situation
  - Associating a sensory pattern with an action to start
- It allows building *routes*, i.e. sequences of recognition-triggered responses
- The local navigation method can be different in each step

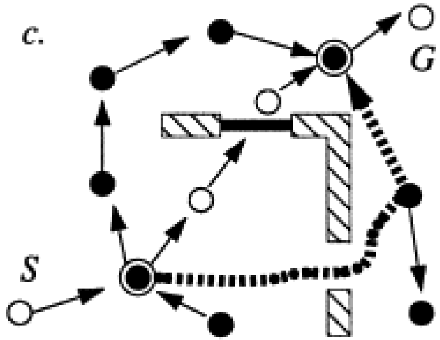
Way finding – topological navigation



- Goal-independent spatial representation, i.e. the same representation can be used for multiple goals
- It requires competences of:
  - Detecting whether two routes pass through the same place -> route integration
  - A collection of integrated routes is a topological representation -> represented by a graph
  - Planning abilities to generate routes for topological graphs

Novel routes over unvisited terrains cannot be generated

Way finding – survey navigation



- It requires competences of:
  - Embedding all known places and their spatial relations into a common frame of reference

Novel routes over unvisited terrains can be generated

Bioinspired robot navigation - navigation hierarchy

Built bottom-up by evolution

		Behavioural prerequisite	Navigation competence
Local navigation	Search	Goal recognition	Finding the goal without active goal orientation
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Not used in robots

Found throughout the animal kingdom

Limited to vertebrates

Classical robot navigation

Local navigation – direction following
Trail following

Inspired by the trail following behaviour of many ant species which lay chemical trails along the ground.

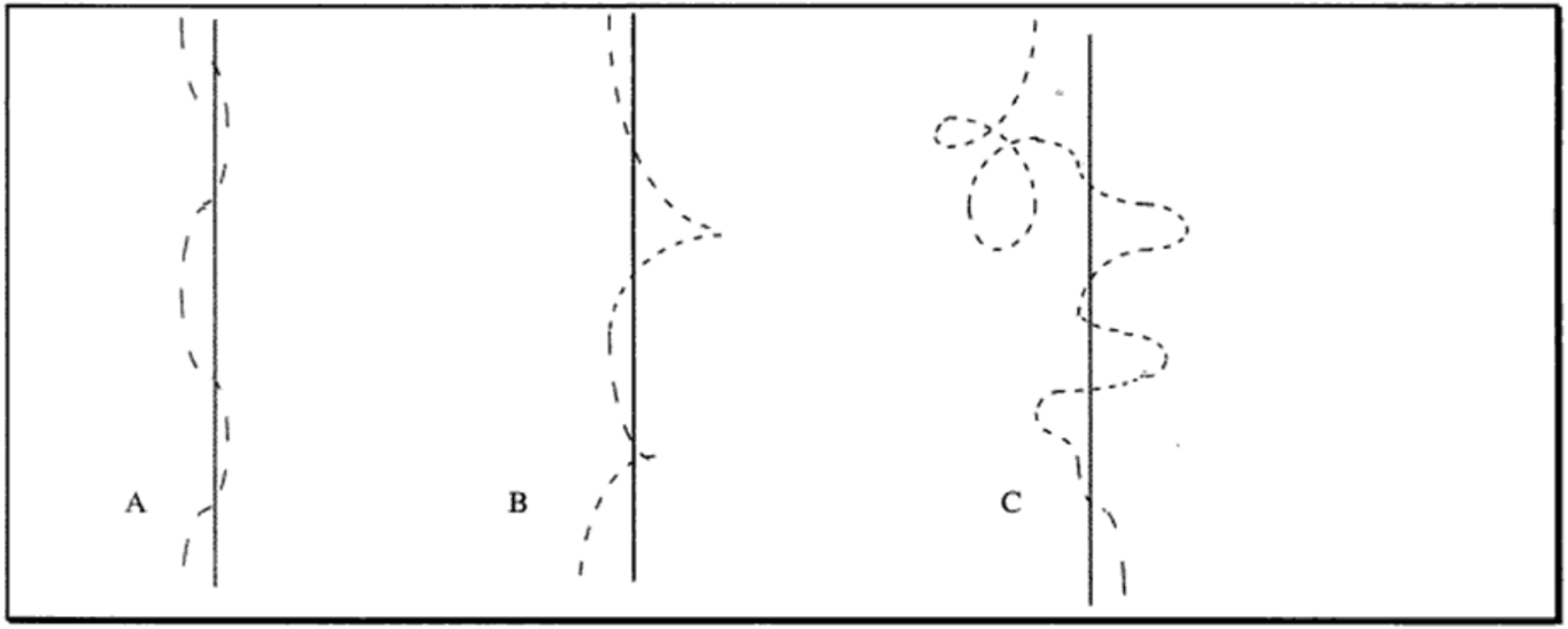


Figure 1: Hangartner's demonstration(1967) of worker ants orientating along a pheromone trail. A shows a normal worker ant following the trail sampling the chemical gradient. B shows a worker ant with its left antenna amputated. C shows a worker ant with its antennae crossed over.

The ants walk in a sinusoidal path through the "vapour tunnel" created by the evaporating chemicals. "*Osmotropotaxis*": The ant detects the concentration of the chemical with both antennae. The concentration difference between left and right determines the turning tendency towards the higher concentration

T. Sharpe, B. Webb, "Simulated and situated models of chemical trail following in ants", in R. Pfeifer, B. Blumberg, J.A. Meyer, S.W. Wilson (Ed.s), *From animals to animats 5, Proc. of SAB98*, MIT Press, Cambridge, MA, 1998, pp.196-204.

Local navigation – direction following
Trail following

- Robot with two chemical sensors simulating the two antennae functions, detecting alcohol vapours
- Sensors mounted on artificial antennaes that extend forwrds and sidewards at a span of 29 cm
- Neural controller implementing osmotropotactic behaviour
- A stronger sensor signal on one side of the robot accelerated the wheel speed on the opposite side, causing steering towards the greater concentration of vapour
- Speed depending on the concentration measured by both sensors, so slower when only faint odour signals.
- Experiments: alcohol trails of various lengths and concentrations laid on the laboratory floor
- Close qualitative correspondence between robot and ant behaviour, e.g., a similar dependence of trail following performance on body axis orientation, speed and antennae span.

T. Sharpe, B. Webb, "Simulated and situated models of chemical trail following in ants", in R. Pfeifer, B. Blumberg, J.A. Meyer, S.W. Wilson (Ed.s), *From animals to animats 5, Proc. of SAB98*, MIT Press, Cambridge, MA, 1998, pp.196-204.

Local navigation – direction following

Trail following

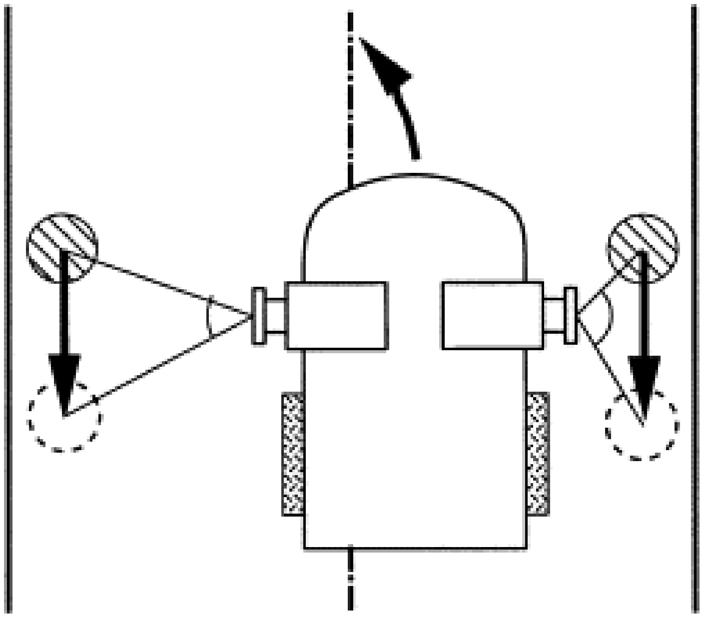
- Trails defined by walls and corridors
- Inspired to insects that balance image motion on their two eyes
- Image motion depends on distance
- Strategy: keeping the overall image motion as constant as possible
- When in narrow passages, insects slow down

D. Coombs and K. Roberts, Centering behavior using peripheral vision, *Proc. of IEEE Conf. on Computer Vision and Pattern Recognition*, Los Alamitos, CA, 1993, pp. 440–451.

Local navigation – direction following

Trail following

- **Bee-bot**: mobile robot with a wide-angle camera with 115° field of view
- Vertical optical flow computed by a gradient method, in the right and left third of the visual field, the vertical (central third ignored)
- The maximal flow value on each side indicated the nearest obstacles
- By balancing the maximal flow on both sides, bee-bot centred its course between the nearest objects.
- Camera actively counter-rotated to stabilize rotation



D. Coombs and K. Roberts, Centering behavior using peripheral vision, *Proc. of IEEE Conf. on Computer Vision and Pattern Recognition*, Los Alamitos, CA, 1993, pp. 440–451.

Local navigation – direction following

Allothetic path integration

SahaBot

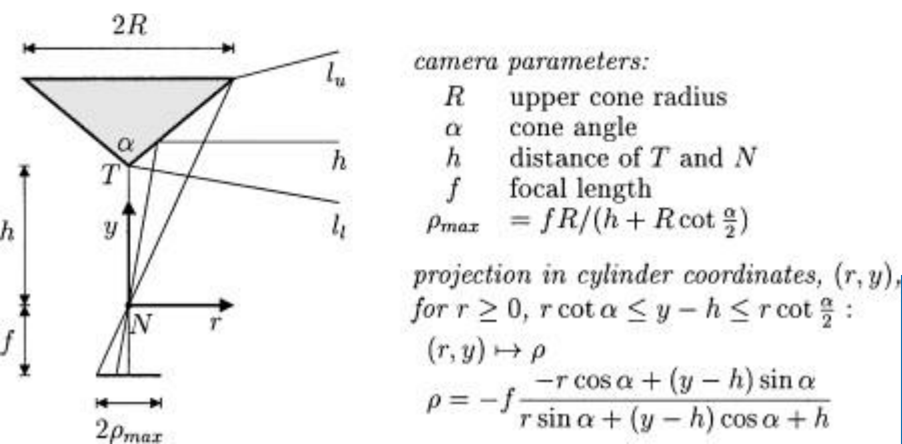
- Ispired to the animal ability to detect the sky polarization pattern for compass orientation
- Inspired to Saharan desert ant *Cataglyphis*
- Polarized light compass for path integration, together with distance estimations from wheel encoder signals
- Three polarization analysers oriented along different polarization planes which mimicked the spatial layout and neural processing of the insect eye.
- The polarization plane at the zenith is perpendicular to the sun's position and thus allows for the determination of the solar meridian.
- Experiments in the Sahara desert
- SahaBot accuracy in the range of ants' one

D. Lambrinos, M. Maris, H. Kobayashi, T. Labhart, R. Pfeifer, R. Wehner, «An autonomous agent anvigating with a polarized light compass«, *Adaptive Behavior* 6, 1997, pp.131-161.

Local navigation – direction following

Allothetic path integration

- Ispired to insects ability not only to estimate their global orientation from visual input, but also the distance travelled
- Distance estimations may be obtained by integrating the optic flow over time
- Mobile robot navigating by path integration using only vision as sensory input
- Two cameras, one at the front and one at the rear of the robot, pointed up to a conical mirror to capture a panoramic image of the environment (2D model of the almost omnidirectional insect eye)
- Two one-dimensional reference images used to generate an interpolated image assuming linear transformation, compared with rear image after motion
- Distance travelled derived from the interpolation parameter and the known distance of the two cameras. Similar procedure to estimate rotation.
- The setup allowed the robot either only to translate or to rotate, not to do both at the same time.



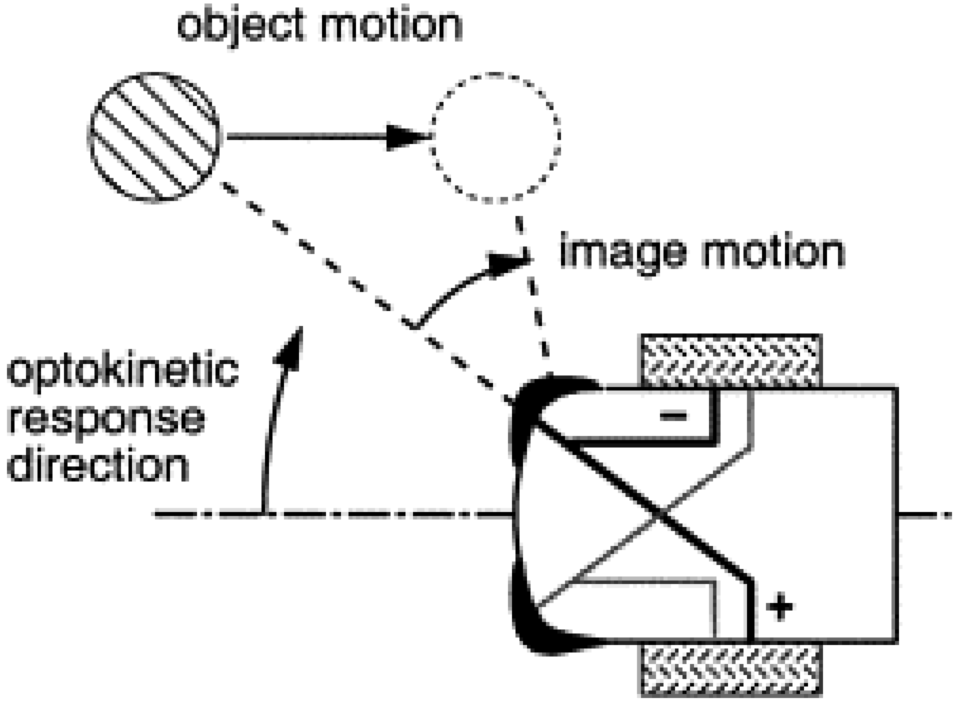
- Experiments: visual path integration based on image motion is indeed possible, not proved superior to path integration based on wheel encoders.

J.S. Chahl, M.V. Srinivasan, "Visual computation of egomotion using an image interpolation technique", *Biological Cybernetics*, 74 (1996), pp. 405-411.

Local navigation – aiming

Valentino Breitenberg's vehicles

- 2 motors and 2 sensors on each side of the robot
- Cross-wide excitatory (vehicle #2) and uncrossed inhibitory connections (vehicle #3)
- These robots find point-like stimuli (light, odour source)



V. Braitenberg, *Vehicles*, MIT Press, Cambridge, MA, 1984.

Local navigation – aiming

Valentino Breitenberg's vehicle #3 – cricket robot

- Inspired to female crickets able to find a conspecific male by turning and approaching the sounds produced by the male (phonotaxis).
- The turning response is elicited when the cricket detects a phase difference between its ears on the two front legs.
- The detection of phase differences is achieved by the anatomy of the auditory apparatus: sound travels to the cricket's tympana either externally or via an internal air-filled tracheal connection. Upon arrival at the tympanum, the sound signals from the two pathways have different phases.
- The phase difference leads to different degrees of amplification or cancellation of the incoming signals in both ears, thus allowing the cricket to detect the direction of the sound source.

B. Webb, "Using robots to model animals: A cricket test", *Robotics and Autonomous Systems*, 16 (1995), pp. 117-134.

Local navigation – aiming

Valentino Breitenberg's vehicle #3

Cricket robot

- Mobile robot with two laterally displaced microphones
- Controller that electronically mimic the relative phase discrimination mechanism and the different internal travel times of the incoming sound signals
- Experiments in a real environment (which is very hard to model and simulate), robot performance very similar to the real cricket: it found an artificial sound source under a variety of conditions, even when the source was located behind an obstacle.
- Extended so that the robot was able to find real crickets instead of an artificial sound source

B. Webb, "Using robots to model animals: A cricket test", *Robotics and Autonomous Systems*, 16 (1995), pp. 117-134.

Local navigation – aiming

Valentino Breitenberg's vehicle #3

- Inspired to flies that orient towards conspicious objects, i.e. black stripes on a uniform background, and approach them
- Inspired to the fly's optomotor response: The fly compensates for disturbances causing a large rotatory image motion by rotating into the direction of the image motion, thus reducing the disturbance
- When an isolated object passes from front to back during flight, the fly compensates for the optic flow created by the object by counter-rotating until the object is brought in front of the insect where it creates almost no image motion
- Thus, both a compensatory optomotor response and an aiming behaviour might be implemented in a common sensomotor controller

S.A. Huber, H.H. Bülthoff, Simulation and robot implementation of visual orientation behaviors of flies, in: R. Pfeifer, B. Blumberg, J.A. Meyer, S.W. Wilson (Eds.), *From Animals to Animats 5, Proceedings of SAB'98*, MIT Press, Cambridge, MA, 1998, pp. 77–85.

Local navigation – aiming

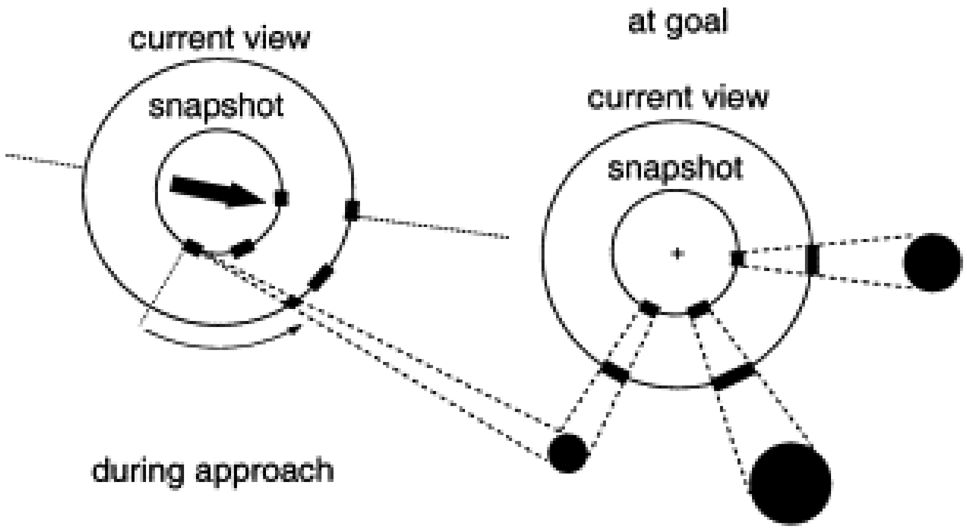
Valentino Breitenberg's vehicle #3

- Mobile robot equipped with a conical mirror camera
- Robot image processing system: relatively detailed one-dimensional model of the insect motion processing pathway
- Motion signals analyzed by an array of Reichardt motion detectors, outputs integrated over each hemisphere.
- Integrated flow from both hemispheres used to control the robot driving direction in the same way as in Braitenberg's #3 vehicle
- Similar to flow-based trail following, but used for aiming
- Experiments: circular arena with black stripes as visual stimuli. The robot produced both fixation and compensatory optomotor behaviour, depending on whether a single isolated stripe or a wide-field pattern was presented.
- The resulting aiming mechanism allowed the robot to find salient objects without requiring sophisticated segmentation techniques.

S.A. Huber, H.H. Bülthoff, Simulation and robot implementation of visual orientation behaviors of flies, in: R. Pfeifer, B. Blumberg, J.A. Meyer, S.W. Wilson (Eds.), *From Animals to Animats 5, Proceedings of SAB'98*, MIT Press, Cambridge, MA, 1998, pp. 77–85.

Local navigation – guidance

- Inspired to ants and bees that are able to use visual guidance (scene-based homing) to find a location which is only defined by an array of locally visible landmarks
- The experimental evidence suggests that these insects store a relatively unprocessed snapshot of the surrounding panorama as seen from the goal.

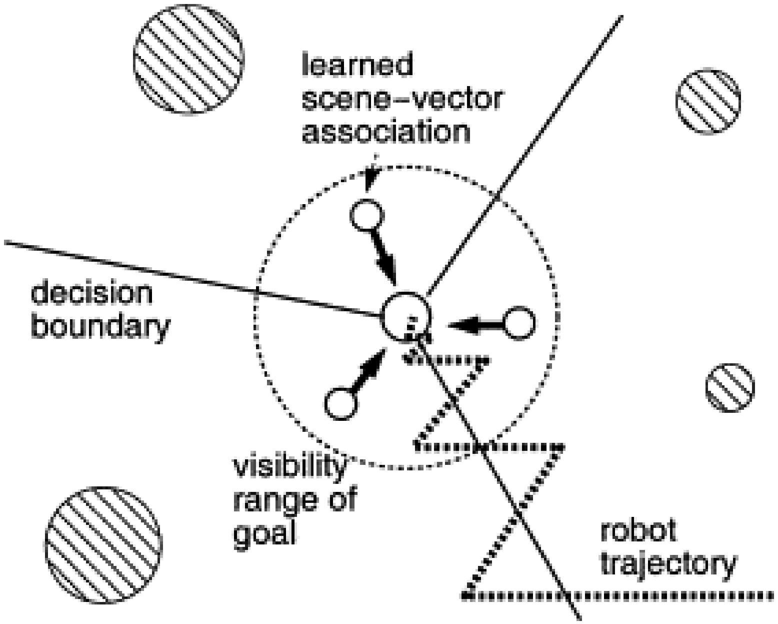


- Omnidirectional views aligned with an external reference direction
- Landmarks as black regions on white background
- Movement direction computed to reduce the perceived difference between the image positions in the snapshot and the current view
- Sum of computed movement directions for all visible landmarks, to give the overall flight direction of the model bee.

B.A. Cartwright, T.S. Collett, "Landmark learning in bees", *Journal of Computational Physiology A*, 151(1983), pp. 521-543.

Way finding – recognition-triggered response

- Inspired to insects, which can associate movement decisions with visual landmarks, and even vertebrates, when a navigation task requires only stereotyped route following
- Mobile robot with rotating camera giving panoramic images
- Learning of associations between compass directions and landmark configurations
- Neural preprocessing stage to determine so-called “focal points” (corners or junctions)
- Around each focal point, extraction of a local landmark view and its compass direction
- Storing of the camera movements leading from one focal point to the next
- A place is given by a sequence of local landmark views and bearings



P. Gaussier, S. ZrehenPerac, “A neural architecture to control artificial animals”, *Robotics and Autonomous Systems*, 16(1995), pp. 291-320

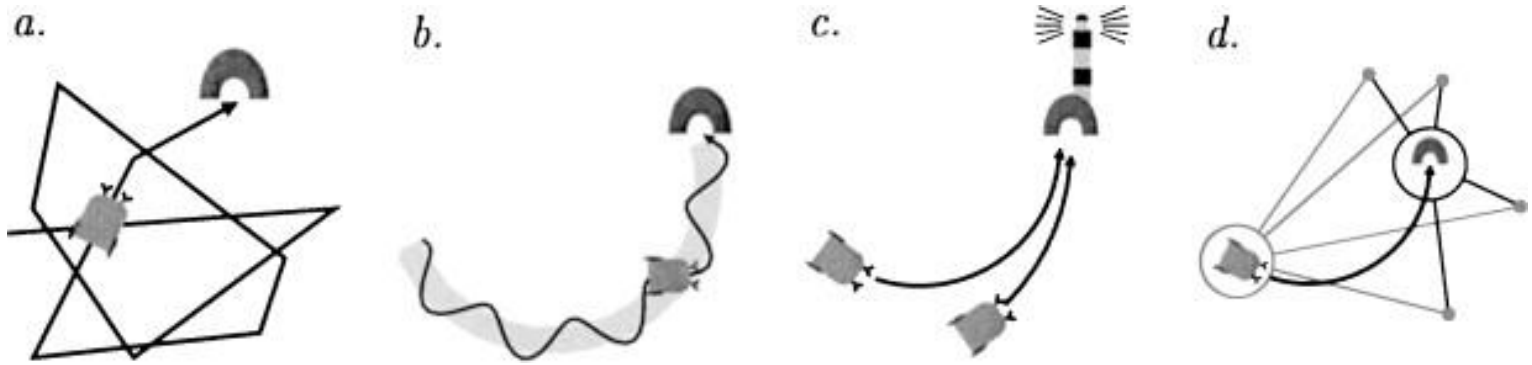
Way finding – topological navigation

- Based on *view graph theory of navigation*: biological navigation behaviour in maze-like environments can be explained if one assumes an underlying topological representation. This so-called "view graph" consists of local views as vertices and their spatial relationships (adjacencies or movement directions) as edges.
- Miniature robot equipped with "two pixel vision", i.e. two infrared sensors looking downward to the textured floor, to explore hexagonal mazes
- Local views = binary patterns on the floor recognized at a maze junction
- Between junctions, the robot travelled by means of corridor following using infrared proximity sensors
- View graph learned by a neural architecture that associated sequences of views with movement decisions
- Experiments: The robot explored a maze of 12 places and 24 "views" in about an hour. Afterwards, the robot was able to find the shortest path between arbitrary pairs of views.

H. Mallot, H. Bülthoff, P. Georg, B. Schölkopf, K. Yasuhara, "View-based cognitive map learning by an autonomous robot", in: F. Fogelman-Soulié, P. Gallinari (Eds.), *Proc. of ICANN'95 — Int. Conf. on Artificial Neural Networks*, Vol. II, EC2, Nanterre, France, 1995, pp. 381–386.

Summary

- Fundamental question: How do I reach the goal?
- Local techniques:



- Global techniques: