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Fuzzy - neural robot navigation

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OUTLINE

- Introduction
- Ways of navigation
- Elements of fuzzy systems, neural networks and information fusion
- Clasical *versus* behavioural approach to robot navigation
- Simulation and experimental results

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Impressive development of computer science, sensors control, communication, smart materials and MEMS created conditions for building

autonomous intelligent robots,
i.e. those which navigate and operate in a real world and in real time
on the basis of multimodal information delivered by sensors of different modalities

The task is extraordinary complex as to the real world is dynamic and unknown

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Two essential reasons for studying mobile robots:

1.Pragmatic reason

Robots are becoming substitutes of humans, extensions of human capabilities, helpers, friends...

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Robotic rower - Sojourner, lauched inside Pathfinder to Mars
in Dec 1996 and landed in July 1997.
It was the first semi-autonomous wehicle on the Matrian surface.

2. Epistemologic (cognitive) reason

Robots are models of what we know about the human mind, the body, and interactions with environment.

Robots are proofs of our conjectures about knowing and acting.

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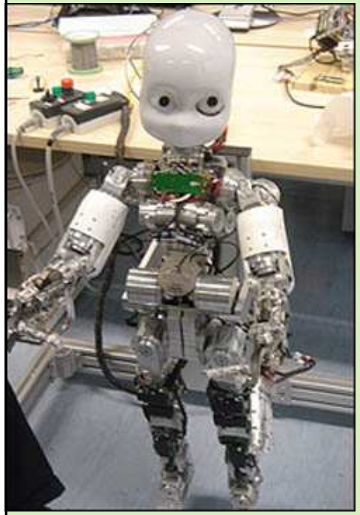

i-CUB robot, the humanoid baby-robot designed as part of the **RobotCub** project

The main focus is to implement biologically sound models of cognition in humanoid robots.

The aim is two-fold :

– furthering our understanding of brain functions

– realizing robot controllers that can learn and adapt from their mistakes

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Autonomous robot is an instantiation of the intelligent system.

Its functionality relies on

sensors
through which the robot
grasps a consistent and coherent view
of its own state
and state of environment,
i.e. a context

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General cognitive capabilities

perception (observation) - **modifies cognition**

cognition (reasoning, decision making) **– modifies actions and adapts perceptions**

Due to these (dual) capabilities the robot can actively explore the environment by re-locating the point of observation.

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Specific cognitive capabilities

- localisation in the environment
- collaboration with others
- goal formulation
- know where to look at and what to do
- know what will likely happen next
- learning from results
- representing knowledge for sharing with others
- self-organization
- planning
- gathering new incentives and skills through interactions with environment
- image recognition, and the more...

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Sensing modalities

major :

seeing
touching
tasting
smelling (olfation)
hearing

specific:

detection of tiny amounts of invisible radiation
detection of movements that are too small or fast for human eye to see
kinesthesis - body movement and balance
proprioception (the perception of body awareness)
and still others

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Intelligent robots cannot be restricted to those employig particular constituents of soft computing techniques (fuzzy logic, neural networks, genetic (memetic) algorithms and probabilistic reasoning) as it is sometimes done.

Hallmarks of intelligent machines are smart interaction and pro-activeness

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NAVIGATION

From Latin: ***navigare*** **=** *sailing, cruising*

a voyage over the see

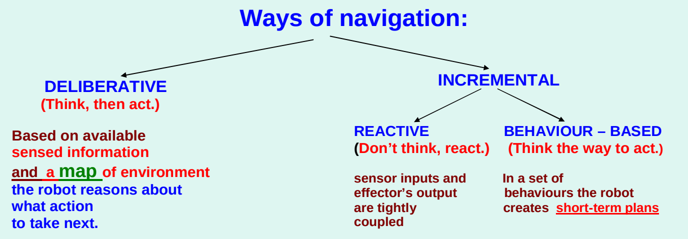
Dead reckoning (*navigation by calculation*). The current position and orientation **is deduced** on the basis of the previous position, motion direction, speed and time.

„Dead“ reckoning or „Ded“ (deduced) reckoning ?

Odometry (*from Greek hodos = lengths, metron = to measure*) - **a kind of dead reckoning** where the length is measured by counting revolutions of wheels

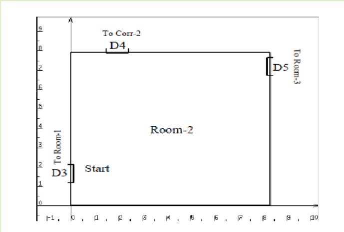
Visual odometry – robot position **is deduced** from the sequence of images.

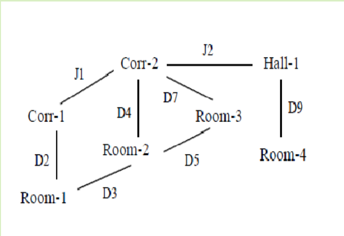
Inertial navigation - the robot position **is calculated** by integration of acceleration.



Global navigation : Robot position is determinated **w.r.t.** **absolute reference system**

Local navigation : Robot position is determinated w.r.t. **other objects** on the basis of interactions with them





Geometric map - represents the objects in accordance with their absolute position

The area has its own coordinale sytem and metric information

Topologic map – is a graph
It captures the structure of the space in terms of connectivity and adjacency

The nods represent places which are in some way significant for navigation.

The edges represent a ways the robot may move from one place to another.

Some aditional information is often used to employ a correct navigation strategy.

E.g., the planner should distinguish between a corridor-like space that can be traversed by wall following, and an open space that should be traversed by dead reckoning.

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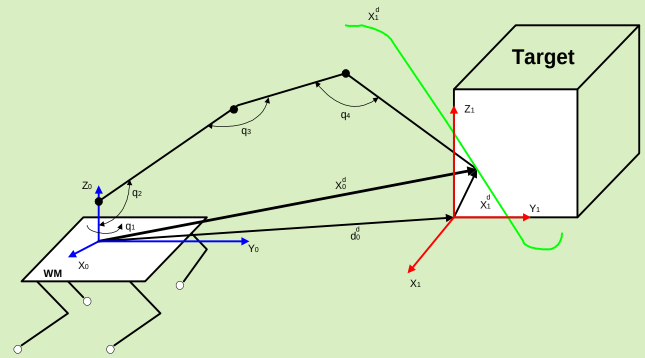
Navigation may include robot positioning w.r.t. a target



$$x_0^d(t) = R_0^1 x_1^d + d_0^1$$

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The map-based navigation is successful in well structured environments

Problem: Map matching
i.e.
finding a correspondence between the map and real environment

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Elements of fuzzy logic

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Fuzzy logic deals with approximate rather than precise reasoning.

In contrast to "crisp“ (clasical) propositional logic,
propositions are represented with degrees of truthfulness.

For example,
the statement, ***today is sunny***, might be 100% true if there are no clouds,
80% true if there are a few clouds, 50% true if it's hazy and 0% true if it rains all day

Caution!
Fuzzy logic and probabilistic logic are **mathematically similar** – **both have true values ranging between 0 and 1 – but conceptually distinct- they have different interpretations.**

Fuzzy logic corresponds to "**degrees of truth**",
while probabilistic logic corresponds to "probability, likelihood".

They represent different models of the same real-world.

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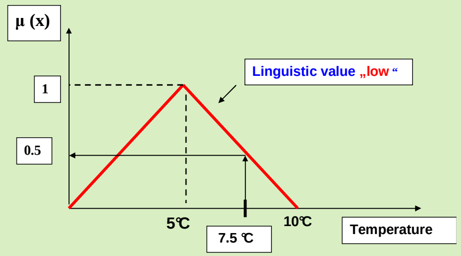
Linguistic value of a crisp quantity



μ (5℃)=1 **μ (7.5℃)= 0.5**

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Logical inference
(process of drawing conclusion)

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Modus ponens for propositional logic

Declaration: *x is A and y is B*
Inference rule: *if x is A and y is B then z is C*
Conclusion: *z is C*

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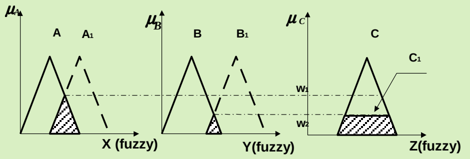
(Generalized) modus ponens for fuzzy inputs

Declaration: *x is A_1 and y is B_1*
Rule: *if x is A and y is B then z is C*
Conclusion: *z is C_1*

If w_1, w_2 are degrees of match between A and A_1, and B and B_1 respectively, then $\min(w_1, w_2)$ is a *degree of the rule fulfilment*.
The output membership μ_{c1} is obtained by clipping down as shown below.



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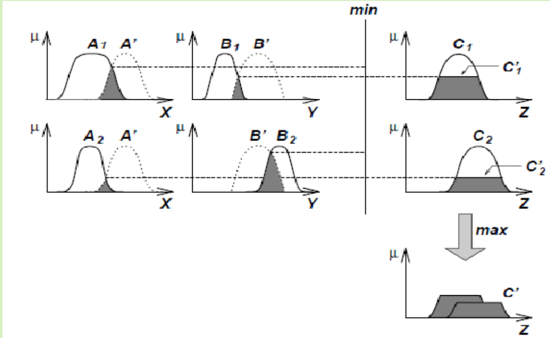
Mamdani inference – a case of two rules and fuzzy inputs and outputs

premise 1 (fact):	x is A' and y is B',
premise 2 (rule 1):	if x is A_1 and y is B_1 then z is
premise 3 (rule 2):	if x is A_2 and y is B_2 then z is
consequence (conclusion):	z is C',



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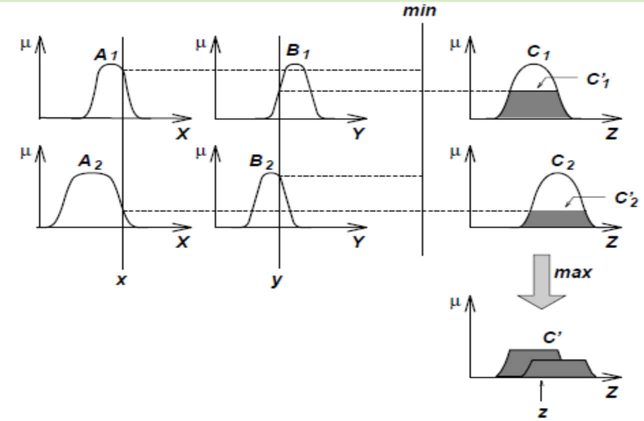
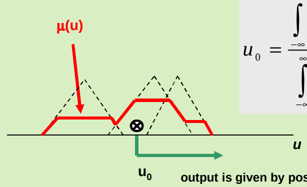
Mamdani inference - a case of crisp inputs



Defuzzyfication
(Centre of Gravity method)
The most frequently used



$$u_0 = \frac{\int_{-\infty}^{\infty} u\mu^*(u)du}{\int_{-\infty}^{\infty} \mu^*(u)du}$$

output is given by position of the centre of gravity

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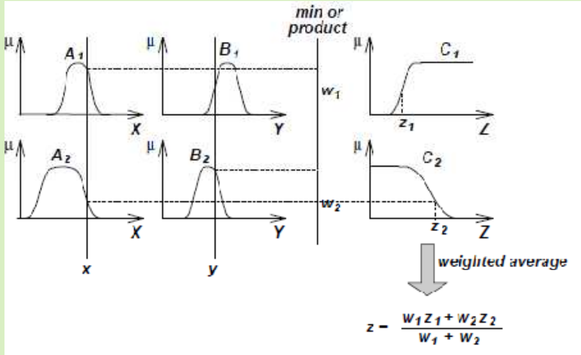
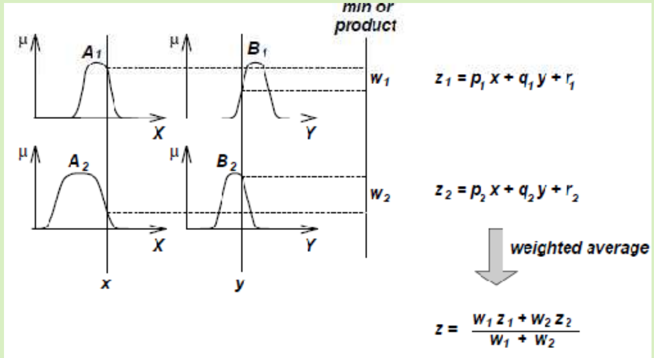
Tsukamoto fuzzy inference - output MFs are monotonic functions.
As a result output is of crisp nature.

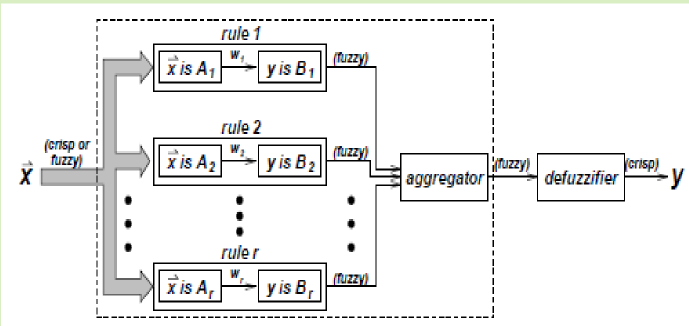


To avoid time consuming deffuzyfication, the „weighted average“ TSK fuzzy inference **is often used**

Typical rule: if x is A and y is B then z=f(x,y)



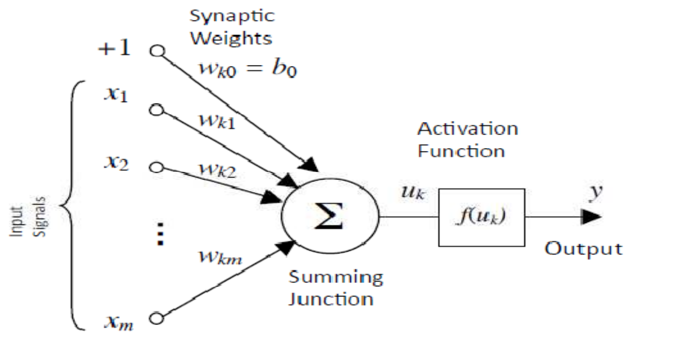
Fuzzy inference over multiple rules



NEURAL NETWOKS

STRUCTURE
AND
LEARNING

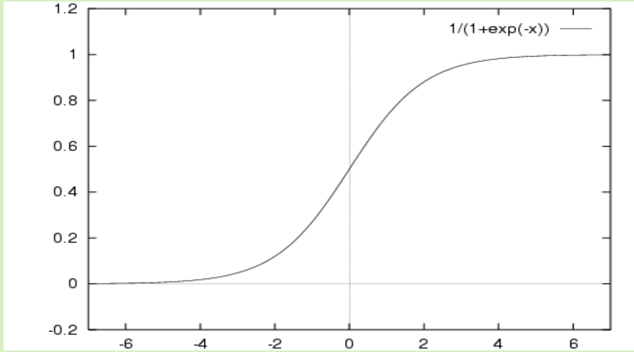
A single neuron



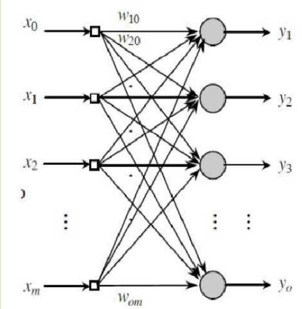
$$y_k = f(u_k) = f\left(\sum_{j=0}^{m} w_{kj} x_j\right)$$

Sigmoidal activation function

$$y = f(x) = \frac{1}{1 + e^{-kx}} \qquad y' = y(1 - y)$$



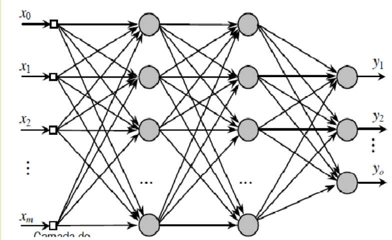
Single-layer Feedforward Networks



$$\mathbf{W} = \begin{bmatrix} w_{10} & w_{11} & \cdots & w_{1m} \\ \vdots & \vdots & \ddots & \vdots \\ w_{o0} & w_{o1} & \cdots & w_{om} \end{bmatrix}$$

$$y_i = f(\mathbf{w}_i.\mathbf{x}) = f(\Sigma_j\, w_{ij}.x_j)\ ,\ j = 1,\ldots,m.$$

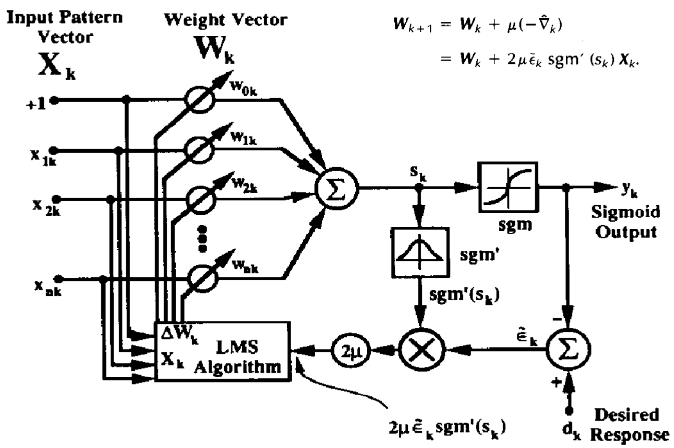
Multilayer Feedforward Network



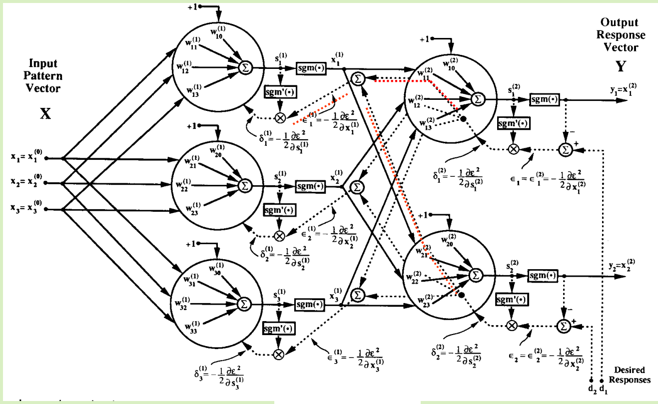
W^k is the synaptic weight matrix of layer *k*

$$\mathbf{y} = \mathbf{f}^3(\mathbf{W}^3\, \mathbf{f}^2(\mathbf{W}^2\, \mathbf{f}^1(\mathbf{W}^1\mathbf{x})))$$

Idea of backpropagation for a sigmoid neuron



$$W_{k+1} = W_k + \mu(-\hat{\nabla}_k)$$
$$= W_k + 2\mu\tilde{\epsilon}_k \, \mathrm{sgm}'(s_k)\, X_k.$$



$$\varepsilon^2 = (d_1 - y_1)^2 + (d_2 - y_2)^2$$

$$\delta_j^{(l)} \triangleq -\frac{1}{2}\frac{\partial \varepsilon^2}{\partial s_j^{(l)}}$$

$$\delta_1^{(2)} = \epsilon_1^{(2)}\, \mathrm{sgm}'(s_1^{(2)}).$$

$$\epsilon_1^{(1)} \triangleq \delta_1^{(2)} w_{11}^{(2)} + \delta_2^{(2)} w_{21}^{(2)}.$$

$$\delta_1^{(1)} = \epsilon_1^{(1)}\, \mathrm{sgm}'(s_1^{(1)}).$$

$$\hat{\nabla}_k = -2\delta_k X_k$$

$$W_{k+1} = W_k + \mu(-\hat{\nabla}_k)$$

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The means of modelling and learning
TSK fuzzy model
is ANFIS

$$\text{If } x \text{ is } A_1 \text{ and } y \text{ is } B_1 \quad \text{THEN} \quad f_1 = p_1 x + q_1 y + r_1$$

$$\text{If } x \text{ is } A_2 \text{ and } y \text{ is } B_2 \quad \text{THEN} \quad f_2 = p_2 x + q_2 y + r_2$$

Outputs of the TSK model are linear functions of inputs.

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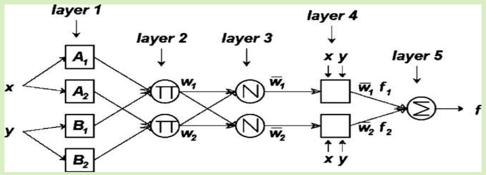
The ANFIS structure for two inputs

Layer 1 (adaptive) MFs (A_1, A_2, B_1, B_2) of the inputs (x,y)
Layer 2 (fix) evaluation of firing strength (e.g. $w_1 = w_x w_y$)
Layer 3 (fix) normalized firing strengths



Layer 4 (adaptive) polynomic functions f_1 and f_2 with adapt. parameters
Layer 5 (fix) f = weighted sum

$$\text{overall output} = \sum_i \overline{w}_i f_i = \frac{\sum_i w_i f_i}{\sum_i w_i}$$

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	Forward Pass	Backward Pass
Premise Parameters	Fixed	Gradient Descent
Consequent Parameters	Least-squares estimator	Fixed
Signals	Node outputs	Error signals

Two passes in the hybrid learning algorithm for ANFIS.

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Classical
versus
behaviour – based
approach to (intelligent) navigation

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CLASSICAL APPROACH
(GOFAI)

- Employs **explicit symbolic representation** of the environment

- **Knowledge and its representation** **is central to** intelligence

Control is decomposed into **functional modules** that process sensor signals in serial stages.

In particular: **Perception module**
Planning module
Actuator module that executes action.

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BEHAVIOUR - BASED APPROACH

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Rodney Brooks from MIT suggested to design a navigator as a set of behaviours.

Brooks (1987):

"Planning is just a way of avoiding figuring out what to do next"

Internal model **is not necessary** for an **agent** to act competently**.**

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BEHAVIORISM versus COGNITIVISM

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Behaviours are basic units for control, representation and learning.

The behaviour has emergent properties which result from interactions.

Contrary to cognitive strategy
BB system does not need any special system performing high-level cognitive tasks.

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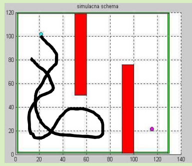
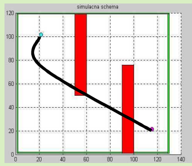
Avoiding obstacles

Robot moves freely with no specific aim, but avoids obstacles.



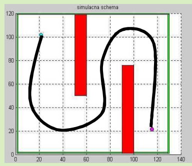
Motion toward the goal

Robot moves toward the goal without paying attention to the presence of obstacles. The only thing of its interests is the direction to the goal.

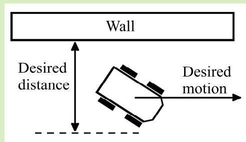


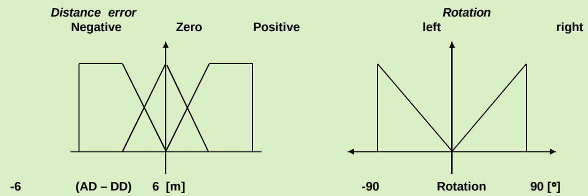
Behaviour fusion

Robot moves toward the goal and simultaenously avoids obstacles ...



Fuzzy description of the wall - following behavior





Robot is required to follow a wall at the desired distance DD, while keeping the orientation of its own body parallel to the wall.

IF (AD – DD) is negative THEN (Rotation is right) AND step forward
IF (AD – DD) is positive THEN (Rotation is left) AND step forward
IF (AD – DD) is zero THEN step forward

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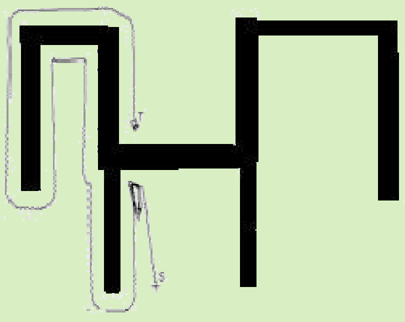
A Pure Wall-following behavior



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AT LEAST THREE LEVELS CAN BE IDENTIFIED:

High level behaviour (a.k.o. a task oriented behaviour)
- goal seeking behaviour (a blend of low level behaviours)

Middle level behaviours
- obstacle avoiding behaviour
- inside a deadlock behaviour
- wall - following behaviour, etc

Low level behaviour may be represented by
- emergency-like behaviour (with **highest priority**).
E.g. The sensor signal is used to directly stop the robot *if an obstacle appears dangerously close* and avoiding is impossible.

This is done by an **atomic action** **(stop, turn by +180 degrees,etc.)**

The behaviours may be easily implemented by Neuro fuzzy learning system.

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IDEA OF SUBSUMPTION ARCHITECTURE
heralded a fundamentally new approach
to get robots more intelligent.

The **overall behaviour is typically broken down** into a set of simpler behaviours, which are loosely co-ordinated.

Every behaviour either selectively **assists** (with variable intensity) or **assumes** control of the subsumed behaviours.

Subsumed behaviours can be inhibited or even supersede
By higher layers.

Contrary to hierarchical control structure,
behaviours appear **concurrently**

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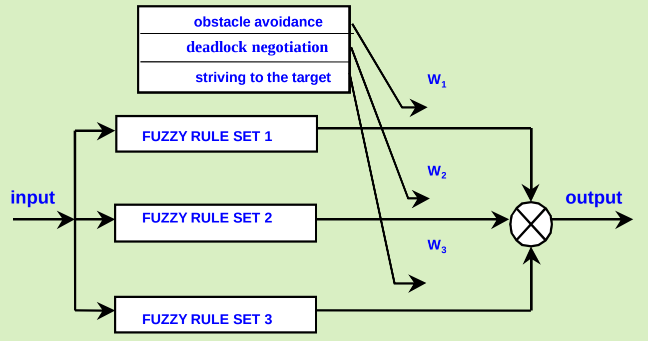
Fusing (blending) behaviours in a subsumption architecture



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Intelligent robot needs fused data

BENEFITS OF SENSOR FUSION

First- the robot obtains more complex information. This is done by fusing ***complementary*** information i.e. **pieces of information which are mutually complemented.**
For instance **images from two cameras looking in different directions**

Second- the robot obtains more accurate information. This is done **by multiple disparate sensors**, which **sense the same quantity**.
For instance**,** sonar and laser range sensors should sense the distance. In this case the **sensors "compete" in a sense**, therefore one can speak about ***competitive fusion***.

Low levels are delineated for fusing pixels and features.

For instance, if grey values of neighbouring pixels are above a given threshold the AND filter is true.

Features are patterns occurring in data
for instance
mean values, correlations, variances,etc.

The low-level fusion uses Kalman filter
as a typical representative

HIGH LEVEL FUSION – a.k.o. DECISION MAKING

High level fusion **combines propositions**.
Each proposition is accompanied with its **certainty value (score)**,
expressing a **measure of truthfulness**.

Examples of propositions

$z_{i.e}$ = there is a cube "i" in the robot's environment "e"
$z_{i.c}$ = object "i" belongs to the cluster "c"
$z_{d,\alpha}$= at the angle "α" there as an obstacle at the distance "d"

Means of the high-level fusion:

- **Probabilistic means (Bayesian statistics)**
- **Dempster-Shafer theory of evidence**
- **Theory of fuzzy sets and fuzzy inferrence**

Higher levels are occupied by more sophisticated procedures of

notion identification and notion interpretation

i.e.
identification of what was observed ?
and
interpretation of what it means to have observed that ?

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Information fusion and map building based on
Dempster-Shaffer theory of evidence

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DEMPSTER–SHAFER THEORY OF EVIDENCE

All independent declarations
about the state of a environment are enumerated
in a set $\Theta = \{E_1, E_2 ... E_n\}$ - frame of discernment.

A certainty - m (*mass* or *basic probability assignment- bpa*) is assigned to both the solitary events (E)
and every element of
the power set – Λ.
(i.e. a set of all subsets of the frame of discernment).

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The Dempster-Shafer inference engine searches
for the total evidence denoted as
"believe (E)" or Bel (E)
that supports the occurence of an event E.

The search is done
by (recursive) application of the
Dempster's rule of combination

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Dempster's rule of combination

Let two sensors S_1 and S_2 with respective bpa-s m_1 and m_2

sense the elements of $\Theta = \{E_1, E_2 ... E_n\}$

Then the total belief

(i.e. the fused evidence supporting the occurrence of the event E)

will be

$$Bel(E) = \frac{\sum_{\forall \{B,C\} \in \Lambda : B \cap C = E} m_1(B) \cdot m_2(C)}{1 - \sum_{\forall \{B,C\} \in \Lambda : B \cap C = \emptyset} m_1(B) \cdot m_2(C)}$$

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Example:

Robot divides its surroundings into a grid. Each cell has assigned a mass – i.e. a measure of confidence of 3 possibilities "occupied", "empty" and "unknown".

Because "unknown" equals to "occupied or empty", (i.e. U = OvE) we have:

Power set =(Φ, O, E, U, OvE, OvU, EvU, OvEvU) = (Φ, O, E, U)

U O U U

Let the measures of confidence are m_s for sensors

and m_o for old evidence (the mass m from the previous iteration)

During mapping the robot calculates m(O) for each cell as follows:

$$m(O) = \frac{m_s(O)m_o(O) + m_s(O)m_o(U) + m_s(U)m_o(O)}{1 - m_s(O)m_o(E) - m_s(E)m_o(O)}$$

IF m(O) is greater then a given confidence level the robot makes a point...

In this way the robot generates a free path.

Quality (of the results) depends on the sensor masses m_s

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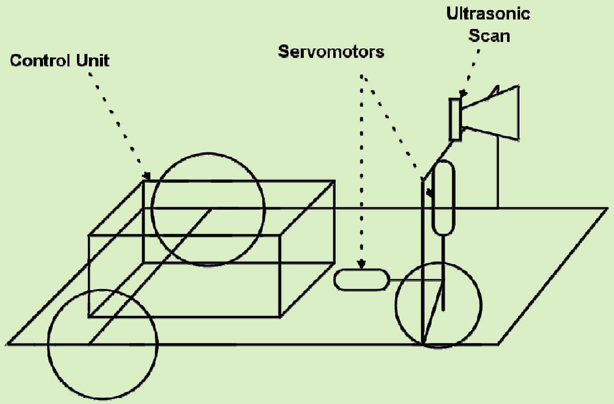
The mobile platform



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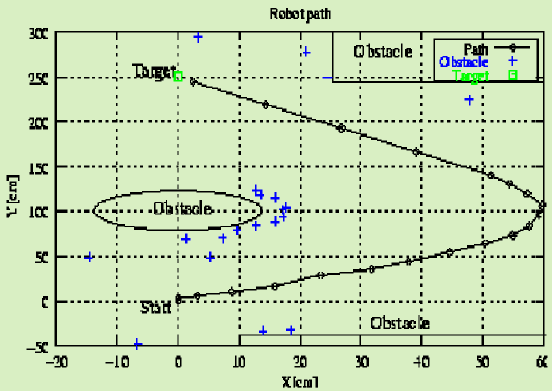
The environment map built by the mobile platfom



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FUZZY- NEURAL NAVIGATION

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An assortment of fuzzy rules

1. If distance is near then step is small
2. If distance is far then step is large
3. If obstackle is right and distance is far then turn left
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.
.
23.
24.

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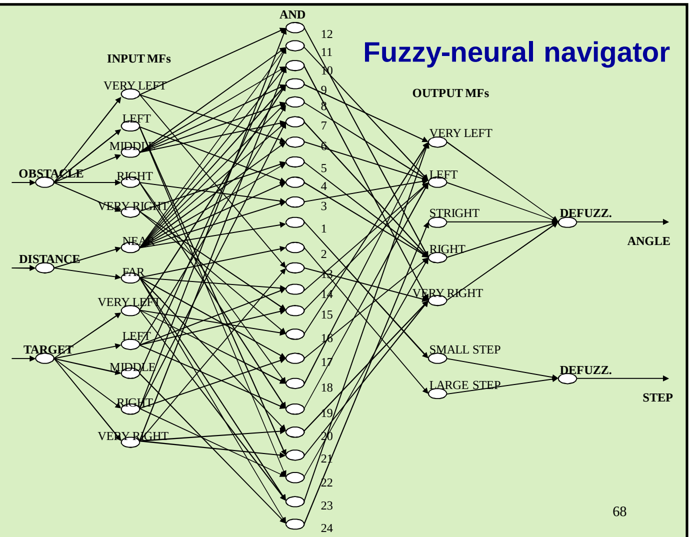
Fuzzy-neural navigator



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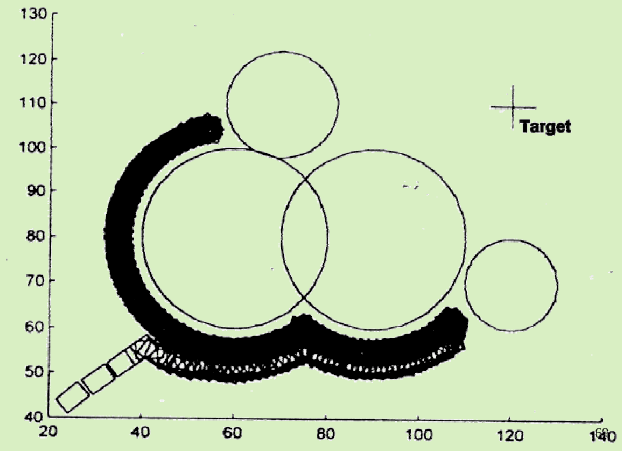
Robot motion before learning



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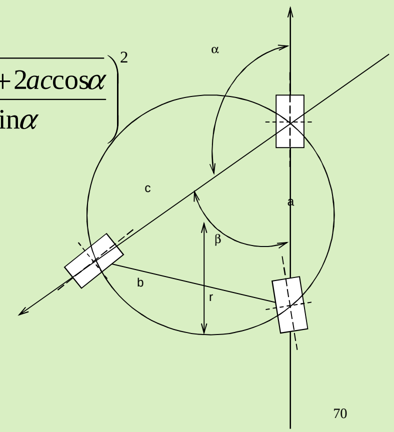
Optimality criterion for unsupervised learning

$$E=(r^d-r)^2=\left(r^d-\frac{\sqrt{a^2+c^2+2ac\cos\alpha}}{2\sin\alpha}\right)^2$$



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Adaptation error

$$E=(r^d-r)^2=\left(r^d-\frac{\sqrt{a^2+c^2+2ac\cos\alpha}}{2\sin\alpha}\right)^2$$

$$\varepsilon = \left(\frac{\partial E}{\partial \alpha}\right)_{\alpha^*}$$

Adaptation error ε **was backpropagated towards the input layer**

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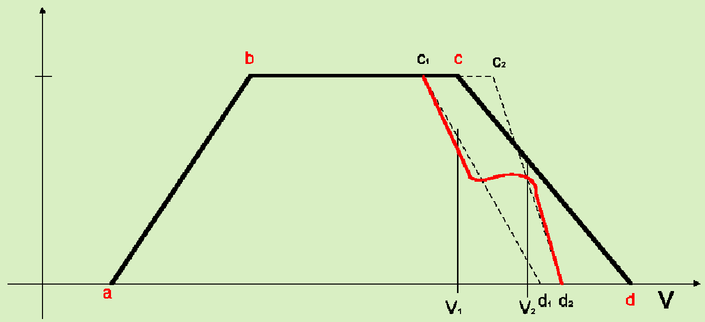
Modification of a trapezoidal MFs during learning



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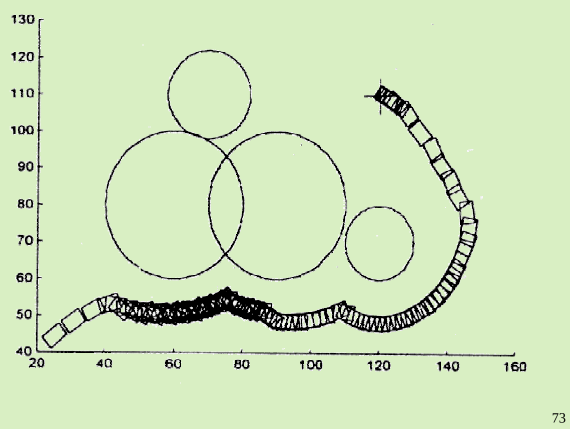
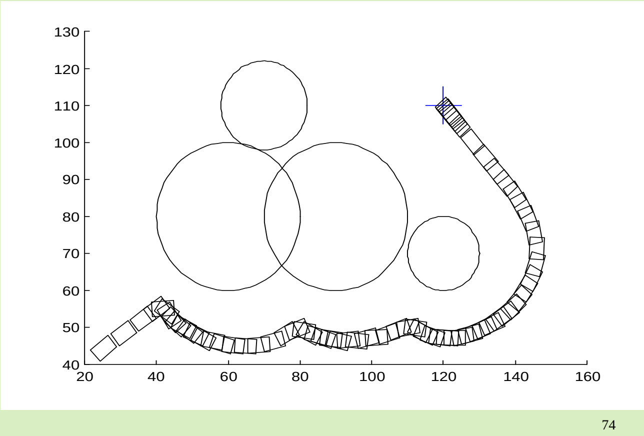
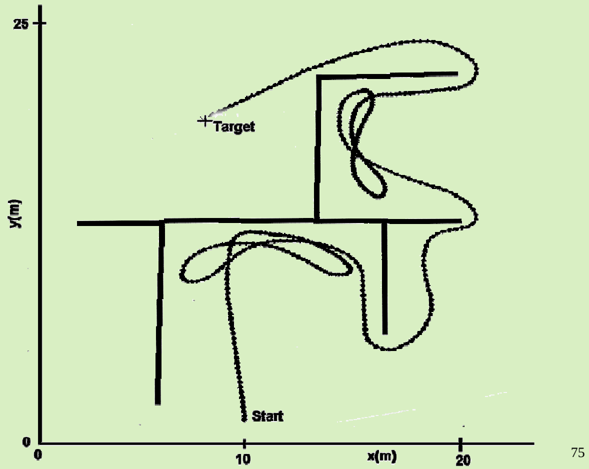
After the rough learning

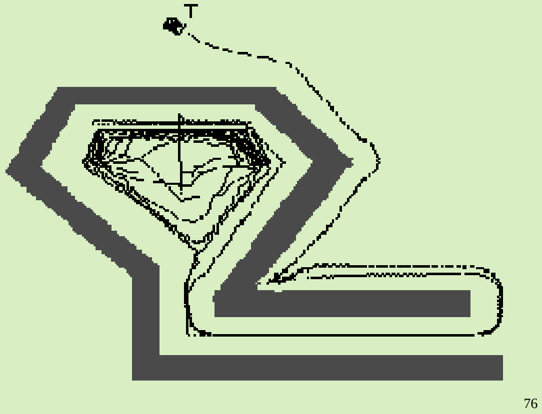


After the fine learning

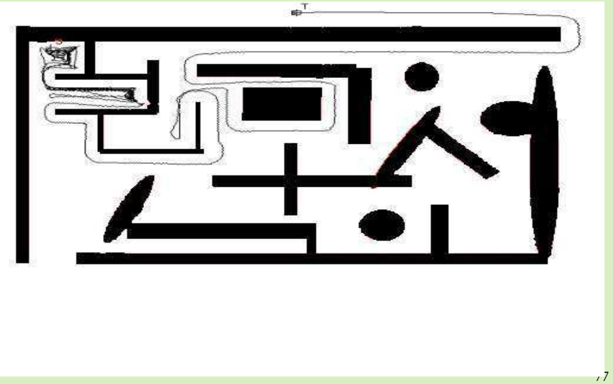




Behaviour in a hollow space



Navigation in a more complex environment



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THANK YOU
FOR YOUR ATTENTION

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