Intelligens Számítási Módszerek
Fuzzy rendszerek, alkalmazáspéldák

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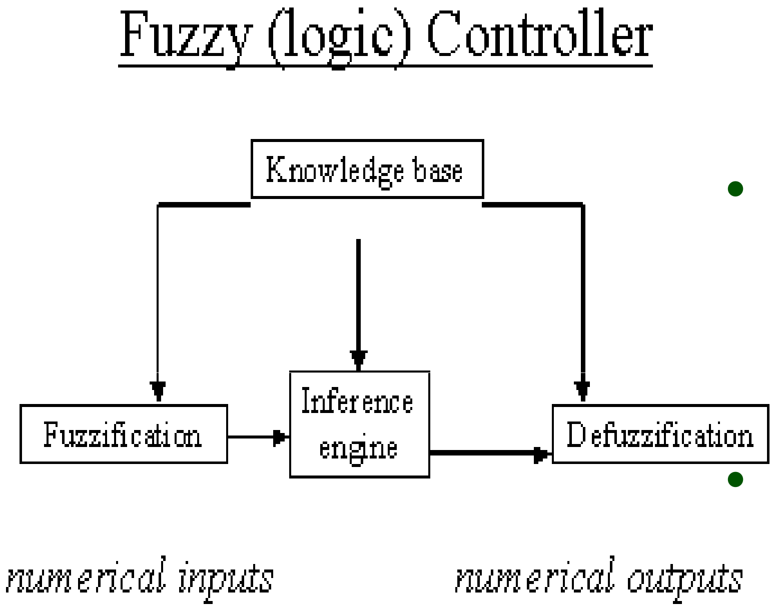
Areas in which Fuzzy Logic was succesfully applied:

- Modelling and control
- Classification and pattern recognition
- Databases
- Expert Systems
- (Fuzzy) hardware
- Signal processing
- Etc.

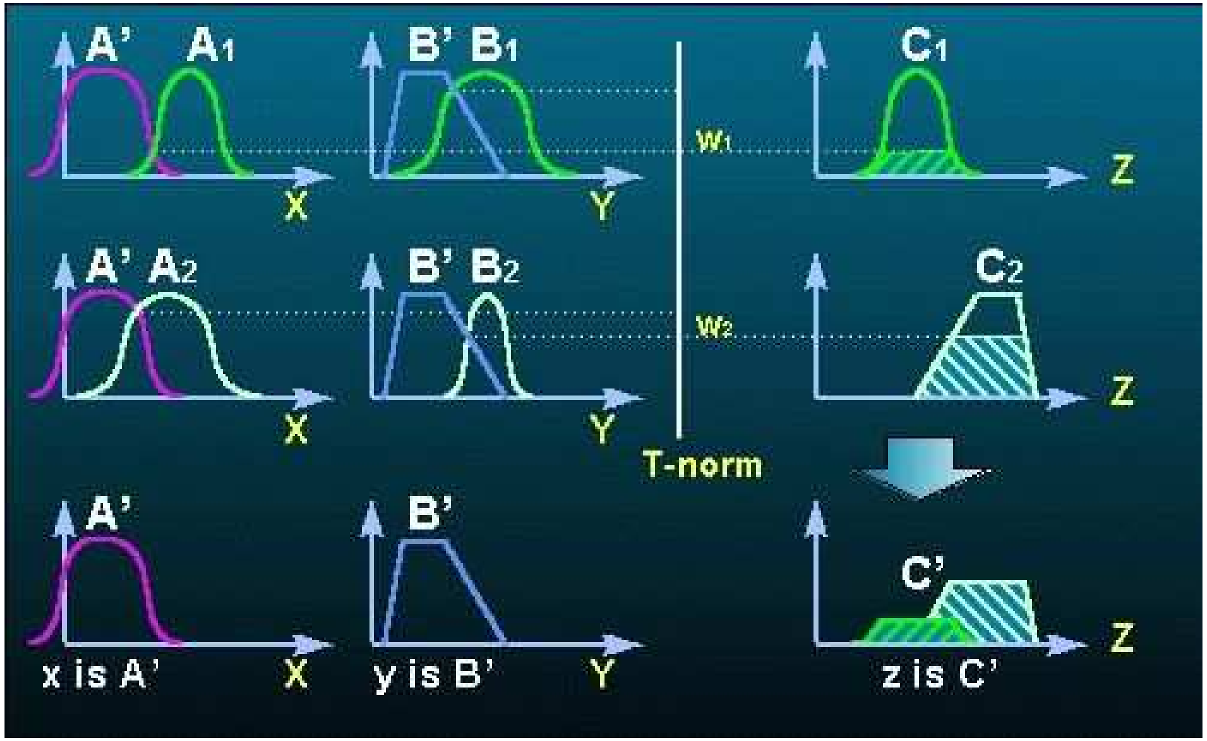
Fuzzy Logic Control



- **Fuzzification:** converts the numerical value to a fuzzy one; determines the degree of matching
- The **knowledge base** contains the
  - **rule base** (fuzzy rules)
  - **data base** (defines membership functions)
- The **inference engine** describes the methodology to compute the output from the input
- **Defuzzification** converts the fuzzy term to a classical numerical value

Fuzzy Inference

- **E.g. Zadeh-Mamdani Type max-min composition**



Planning of Fuzzy Controllers

Determination of fuzzy controllers = determination of the antecedents + consequents and the rules

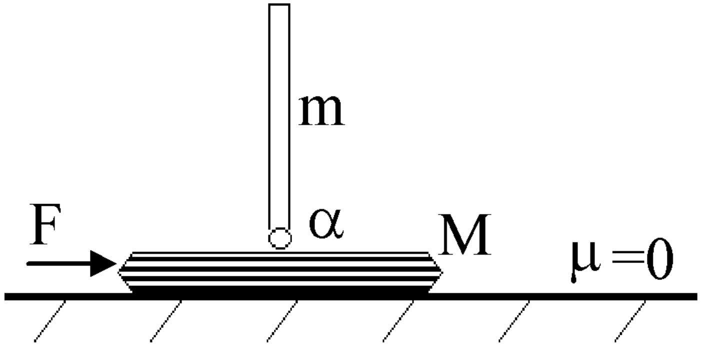
- **Antecedents:**
  - **Selection of the input dimensions**
  - **Determination of the fuzzy partitions for the inputs**
  - **Determination of the parameters for the fuzzy variables**
- **Consequents:**
  - **Determination of the fuzzy partitions for the outputs**
  - **Determination of the parameters**
- **Rules:**
  - **Determination of the rules in the form:**
    If antecedent term$_1$ **and … and** antecedent term$_n$ **then** consequent

Balancing of an inverted pendulum

$$(m+M)\cdot\sin^2(\alpha)\cdot l\cdot\ddot{\alpha}+m\cdot l\cdot\sin(\alpha)\cdot\cos(\alpha)\cdot(\dot{\alpha})^2-(m+M)\cdot g\cdot\sin(\alpha)=-F\cdot\cos(\alpha)$$

- where

g	is the gravitational constant,
l	is the length of the pole,
m	is the mass at the head of the pendulum,
M	is the mass at the foot point of the pendulum,
α	is the angle of the pendulum,
$\dot{\alpha}$	is the angular velocity, and
F	is the force to control the pendulum stay upright



Balancing of an inverted pendulum

- **Fuzzy model**

  If the angle α is A_1 and the angular velocity $\dot{\alpha}$ is A_2 than let the force F be B

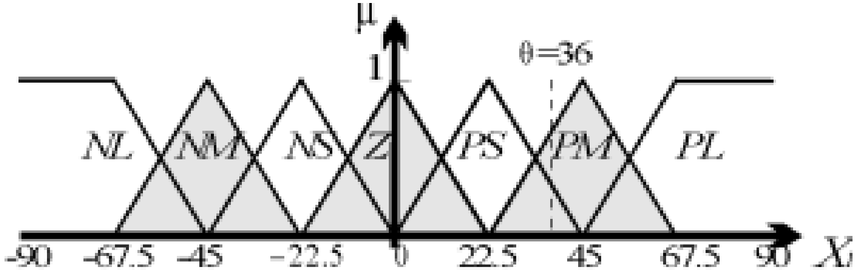
- **E.g:**

  If the angle α is *zero* and the angular velocity $\dot{\alpha}$ is *zero* than let the force F be *zero*

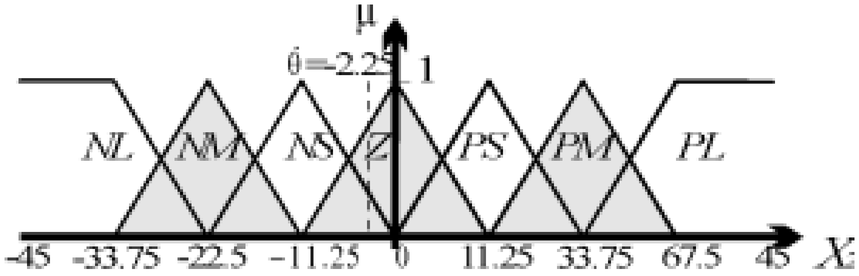
Balancing of an inverted pendulum

Linguistic terms

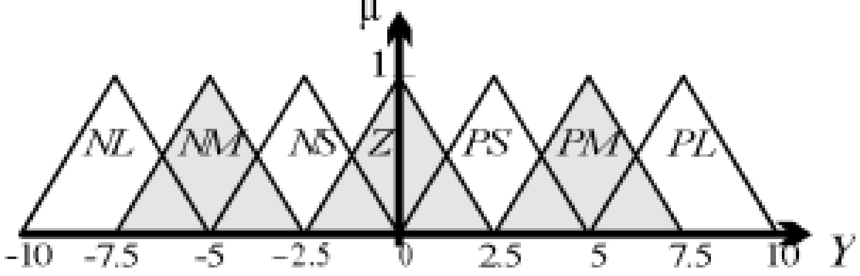
- The linguistic terms of the angle α (X_1):



- The linguistic terms of the angular velocity $\dot{\alpha}$ (X_2):



- Linguistic terms of the force F(Y).



Balancing of an inverted pendulum

Rule base

R :

		$\alpha =$						
		NL :	NM :	NS :	Z :	PS :	PM :	PL :
$\alpha' =$	NL :			PS	PL			
	NM :				PM			
	NS :	NM		NS	PS			
	Z :	NL	NM	NS	Z	PS	PM	PL
	PS :				NS	PS		PM
	PM :				NM			
	PL :				NL	NS		

Balancing of an inverted pendulum

Rule base

R :

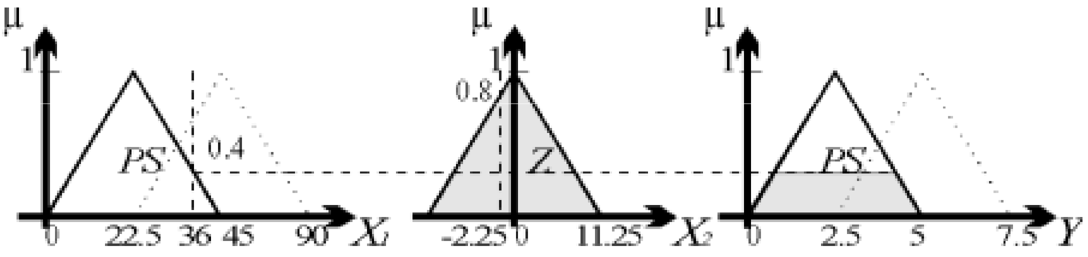
		$\alpha =$						
		NL :	*NM :*	*NS :*	*Z :*	*PS :*	*PM :*	*PL :*
$\alpha' =$	*NL :*	*NS*	*Z*	*PS*	*PL*	*PL*	*PL*	*PL*
	NM :	*NM*	*NS*	*Z*	*PM*	*PM*	*PL*	*PL*
	NS :	*NM*	*NS*	*NS*	*PS*	*PS*	*PM*	*PL*
	Z :	*NL*	*NM*	*NS*	*Z*	*PS*	*PM*	*PL*
	PS :	*PL*	*NM*	*NS*	*NS*	*PS*	*PS*	*PM*
	PM :	*NL*	*NL*	*NM*	*NM*	*Z*	*PS*	*PM*
	PL :	*NL*	*NL*	*NL*	*NL*	*NS*	*Z*	*PS*

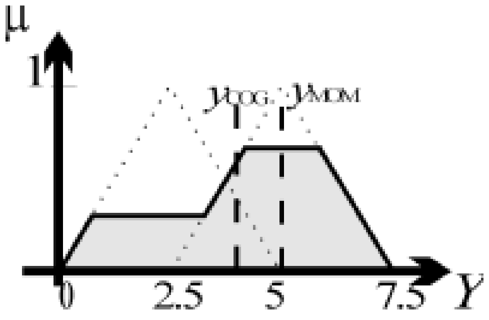
Balancing of an inverted pendulum

Example of inference

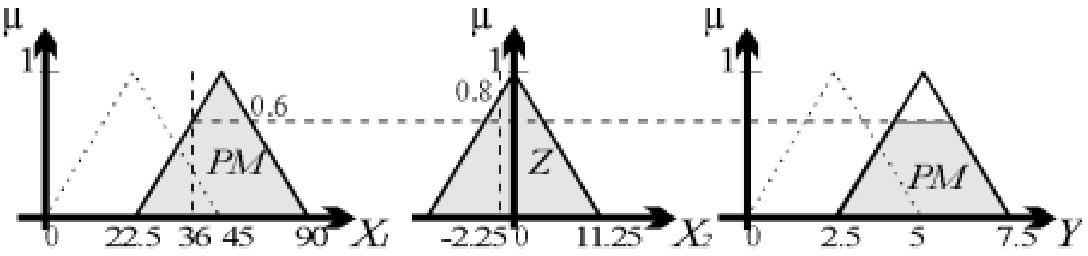
- **Observation $\alpha = 36^\circ$, $\dot{\alpha} = -2.25^\circ/s$.**
- **Fired rules:**

  R_1: If α = PS and $\dot{\alpha}$ = Z then F = PS



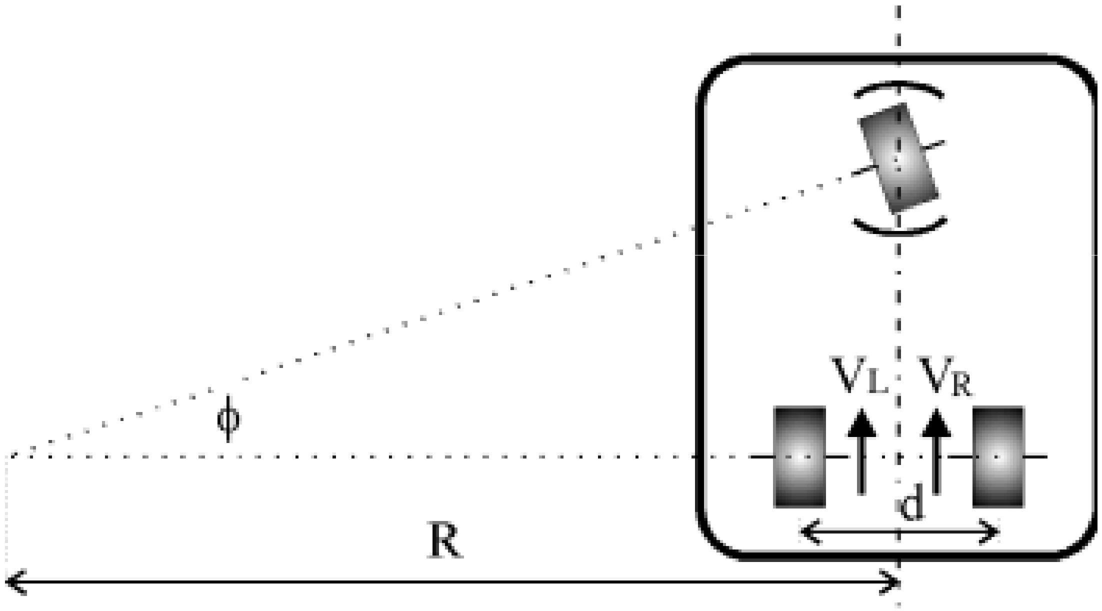


- **R_2: If α = PM and $\dot{\alpha}$ = Z then F = PM**



Path tracking of an automated guided vehicle

- **AGV with fixed directional wheel configuration, with differential steering**



Path tracking of an automated guided vehicle

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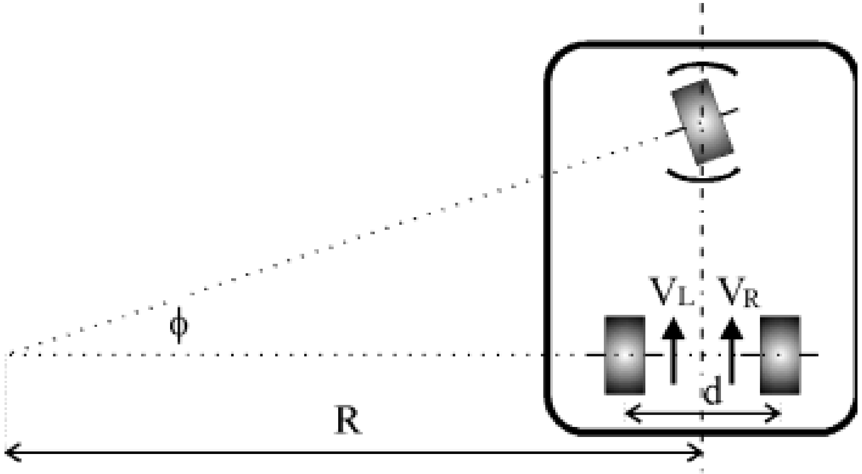
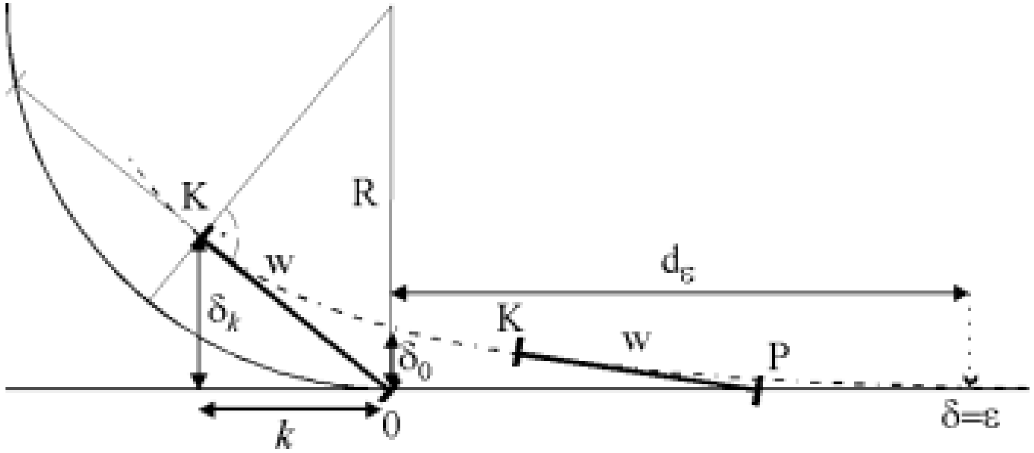


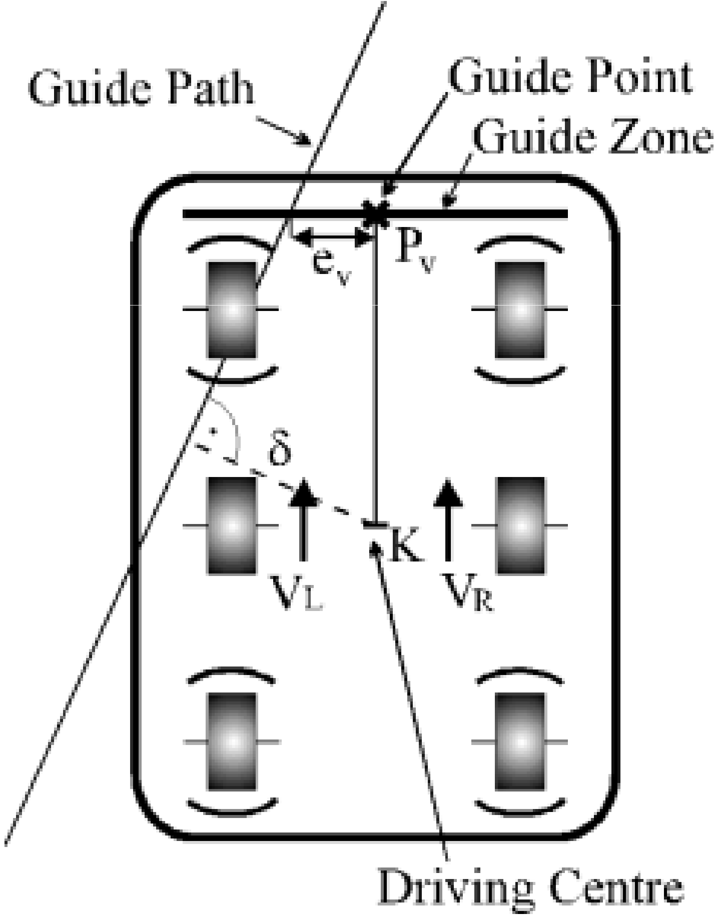
- **Trajectory of the driving centre of a differential steered AGV using the guide point based tracking strategy.**



Path tracking of an automated guided vehicle

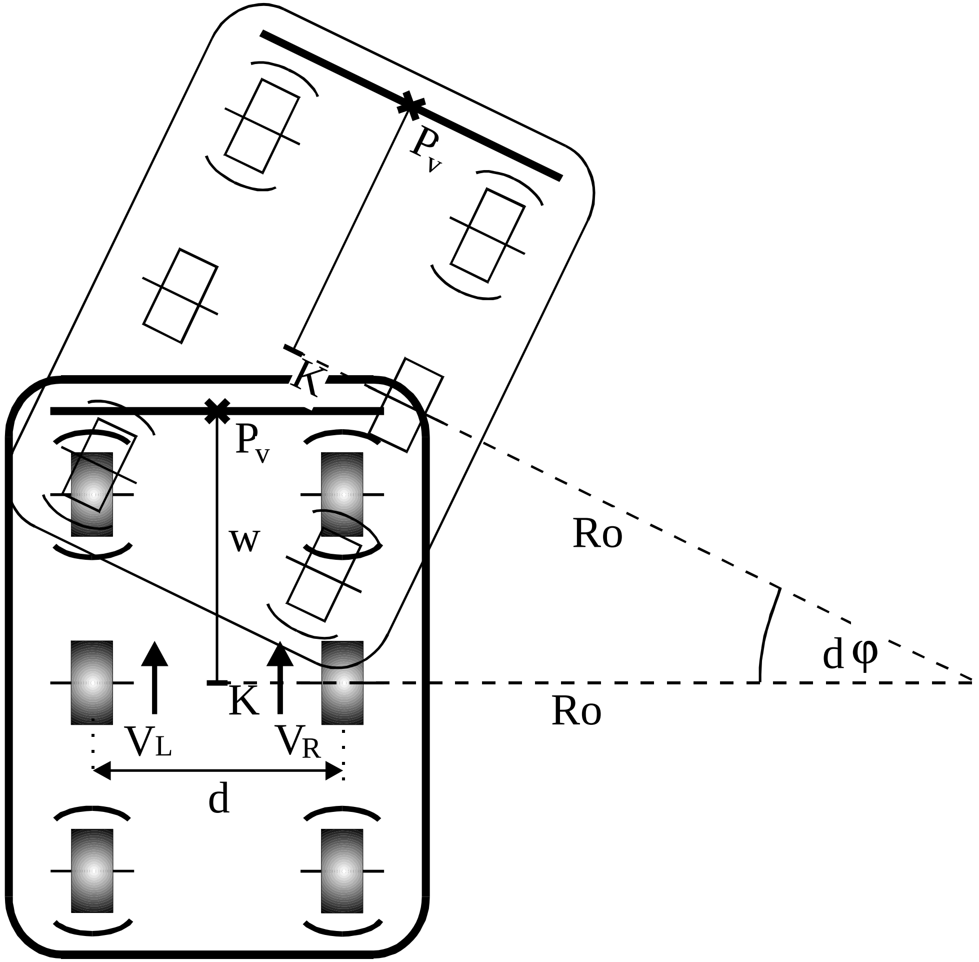
- **For finding better trajectory concept of *guide zone* will be used**

Differential steered AGV with guide zone:



Path tracking of an automated guided vehicle

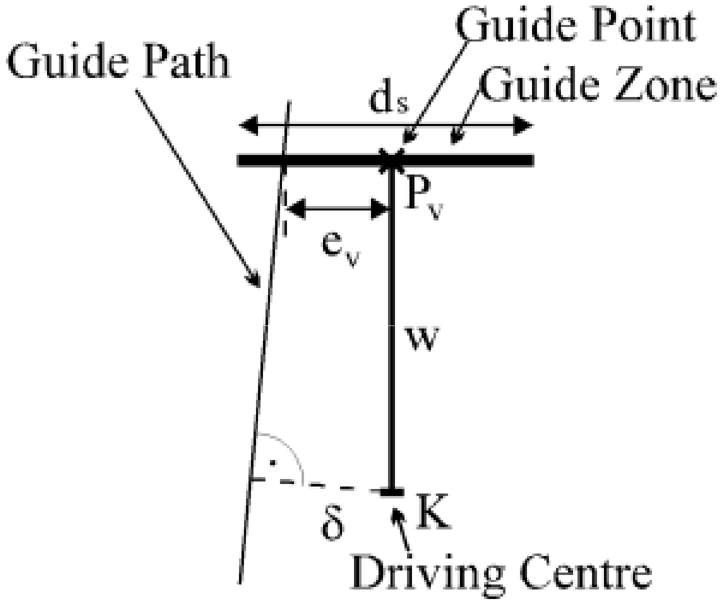
- **Analytic model of the AGV motion:**

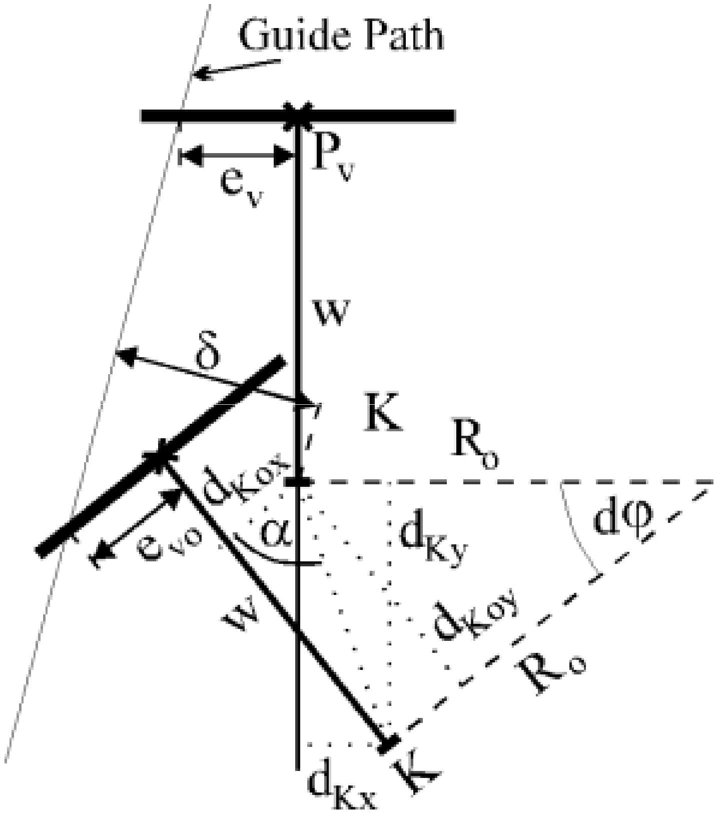


$$s_L = V_L \cdot dt \quad s_R = V_R \cdot dt$$

Path tracking of an automated guided vehicle

- **Analytic model of the AGV motion:**





Calculation of the estimated momentary path tracking error

Path tracking of an automated guided vehicle

- **Analytic model of the AGV motion:**

$$d\varphi = \frac{s_L - s_R}{d} \qquad R_o = d \cdot \frac{s_L + s_R}{2 \cdot (s_L - s_R)}$$

$$dK_{ox} = R_o \cdot (1 - \cos(d\varphi))$$

$$dK_{oy} = R_o \cdot \sin(d\varphi) \qquad \alpha = \arctan\left(\frac{dK_{oy}}{dK_{ox}}\right)$$

$$dK = \sqrt{dK_{ox}^2 + dK_{oy}^2}$$

$$dK_x = -dK \cdot \cos(\alpha + d\varphi)$$

$$dK_y = -dK \cdot \sin(\alpha + d\varphi)$$

$$e_{vox} = -dK_x + w \cdot \sin(d\varphi) + e_{vo} \cdot \cos(d\varphi)$$

$$e_{voy} = -dK_y + w \cdot \cos(d\varphi) - e_{vo} \cdot \sin(d\varphi)$$

$$\delta_m = e_v \text{ - } w \cdot \left(\frac{e_v - e_{vox}}{w - e_{voy}}\right) \qquad \xi = \arctan\left(\frac{e_v - e_{vox}}{w - e_{voy}}\right)$$

$$\delta = \delta_m \cdot \cos(\xi)$$

where:

e_v	**the distance between the guide path and the guide point (measured on the guide zone),**
e_{vo}	**the previous value of e_v,**
s_R	**move of the AGV measured on the right wheel,**
s_L	**on the left wheel,**
w	**distance of the guide point and the driving centre,**
d	**distance of the two wheels,**
δ	**the estimated momentary path tracking error, we are looking for**

Path tracking of an automated guided vehicle

- **Observations of the controller:**
  - **ev** the distance between the guide path and the guide point (measured on the guide zone),
  - δ the estimated momentary path tracking error
- **Conclusions of the controller:**

Momentary manoeuvres:

- speed (**Va**),
- steering (**Vd**).

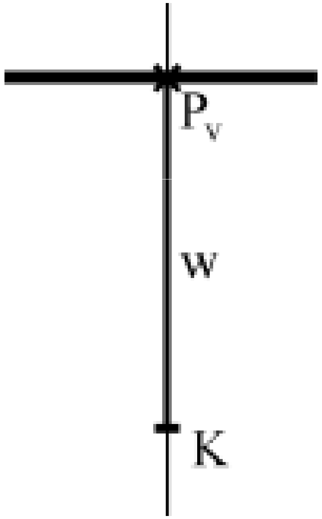
$$V_a = \frac{V_L + V_R}{2}$$

$$V_d = V_L - V_R$$

Path tracking of an automated guided vehicle

Rule base e.g.

If the *distance between the guide path and the guide point* (e_v) is *Zero* and *estimated path tracking error* (δ) is *Zero* then the *steering* (V_d) is *Zero* and the *speed* (V_a) is *Large*

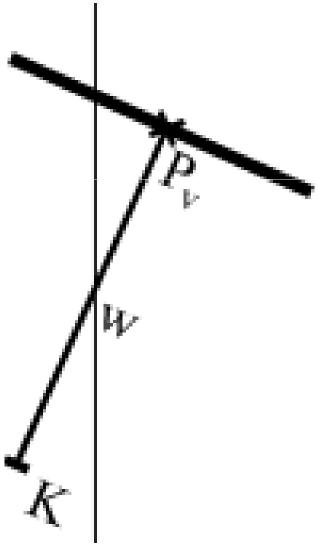


If e_v = Z And δ = Z Then V_d = Z And V_a = L

Path tracking of an automated guided vehicle

Rule base e.g.

If the *distance between the guide path and the guide point* (e_v) is *Positive Middle* and *estimated path tracking error* (δ) is *Negative Middle*
then the *steering* (V_d) is *Zero* and the *speed* (V_a) is *Middle*

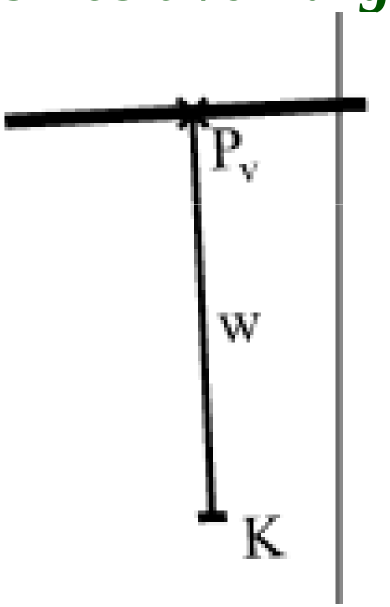


$$\text{If } e_v = \text{PM And } \delta = \text{NM Then } V_d = \text{Z And } V_a = \text{M}$$

Path tracking of an automated guided vehicle

Rule base e.g.

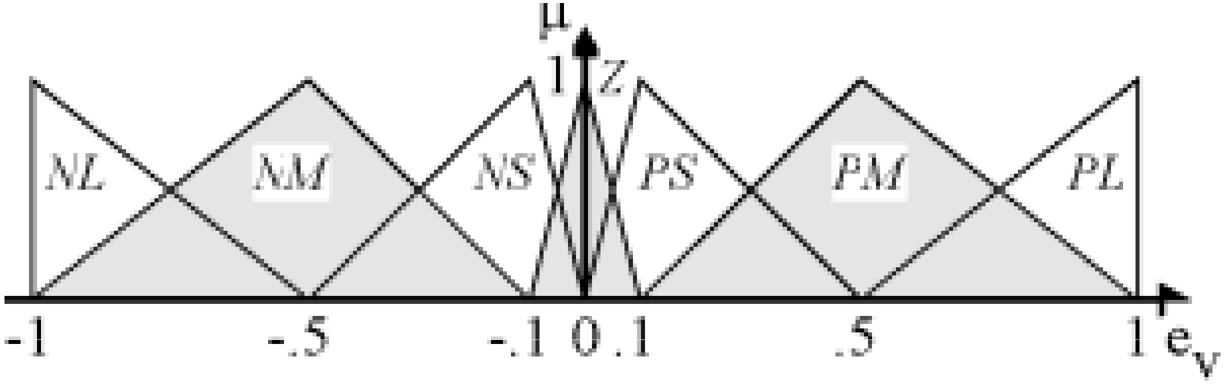
If the *distance between the guide path and the guide point* (e_v) is *Negative Large* and *estimated path tracking error* (δ) is *Negative Middle* then the *steering* (V_d) is *Positive Large* and the *speed* (V_a) is *Small*



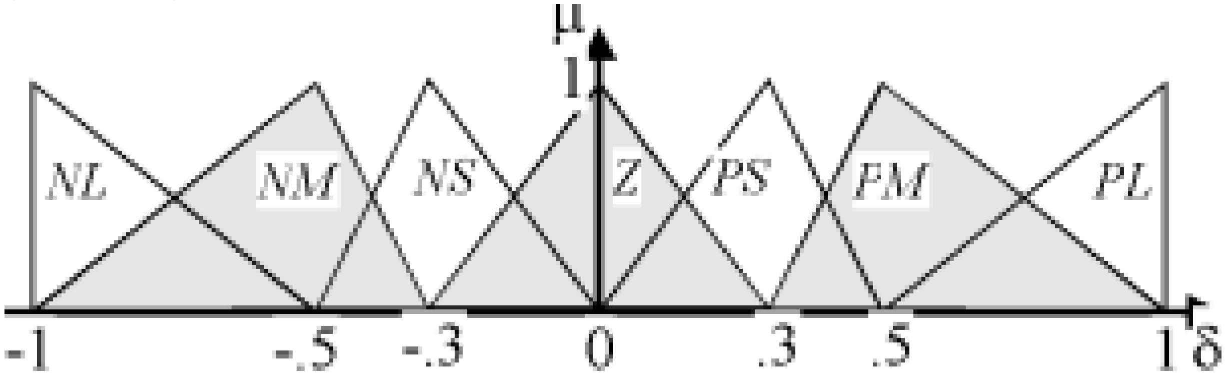
If e_v = NL And δ = NM Then V_d = PL And V_a = S

Path tracking of an automated guided vehicle

- **Antecedent Fuzzy partitions**
  - The fuzzy partition of the distance between the guide path and the guide point (e_v) primary fuzzy sets (linguistic terms):



  - The fuzzy partition of the estimated path tracking error (δ) primary fuzzy sets:



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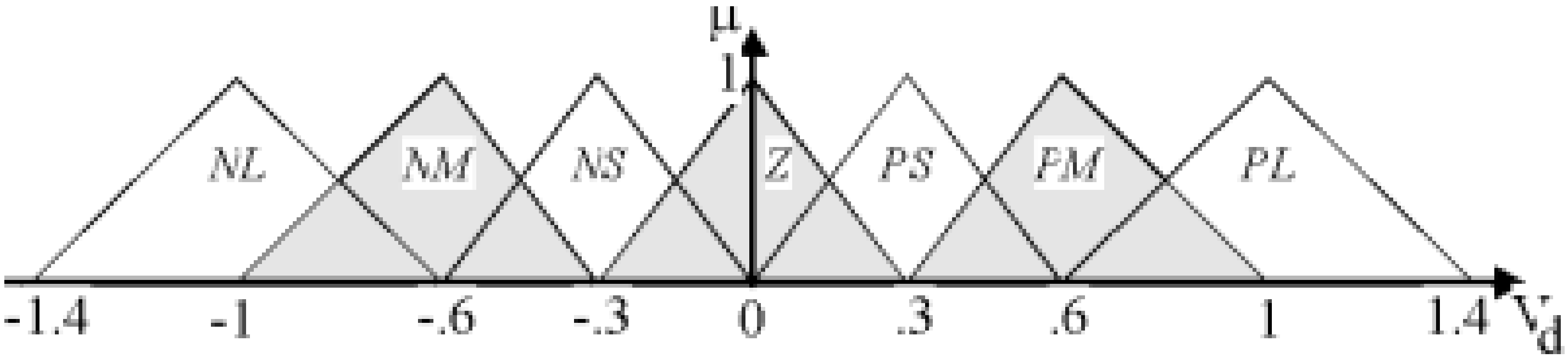
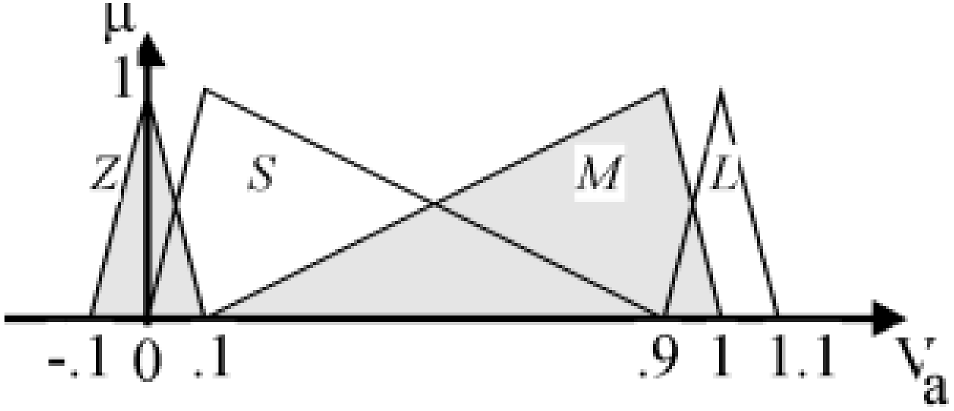
Path tracking of an automated guided vehicle

- **Consequent Fuzzy partitions**
  - The fuzzy partition of the steering (V_d) primary fuzzy sets:



  - The fuzzy partition of the speed (V_a) primary fuzzy sets:



Path tracking of an automated guided vehicle

Rule base

- For the **steering** (**R_{Vd}**):

R_{Vd}: $e_v =$

$\delta =$

	NL :	NM :	NS :	Z :	PS :	PM :	PL :
NL :	PM	PS	Z	Z	NL	NL	NL
NM :	PL	PS	PS	PS	PS	Z	NL
NS :	PL	PM	PS	PS	Z	Z	NL
Z :	PL	PM	PS	Z	NS	NM	NL
PS :	PL	Z	Z	NS	NS	NM	NL
PM :	PL	Z	NS	NS	NS	NS	NL
PL :	PL	PL	PL	Z	Z	NS	NM

- For the **speed** (**R_{Va}**):

R_{Va}: $e_v =$

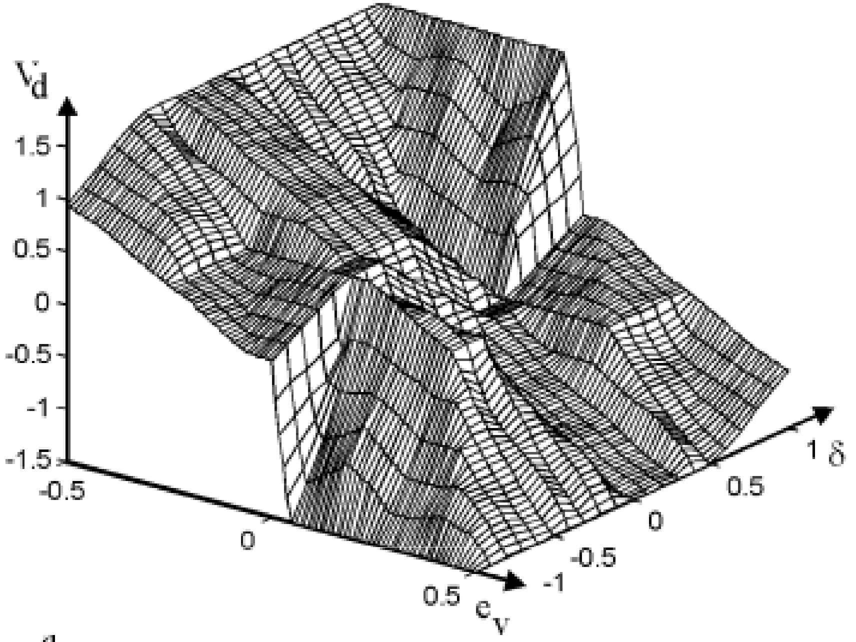
$\delta =$

	NL :	NM :	NS :	Z :	PS :	PM :	PL :
NL :	M	S	S	S	S	Z	Z
NM :	S	M	M	M	M	M	S
NS :	Z	S	L	L	L	M	S
Z :	S	M	L	L	L	M	S
PS :	S	M	L	L	L	S	Z
PM :	S	M	M	M	M	M	S
PL :	Z	Z	S	S	S	S	M

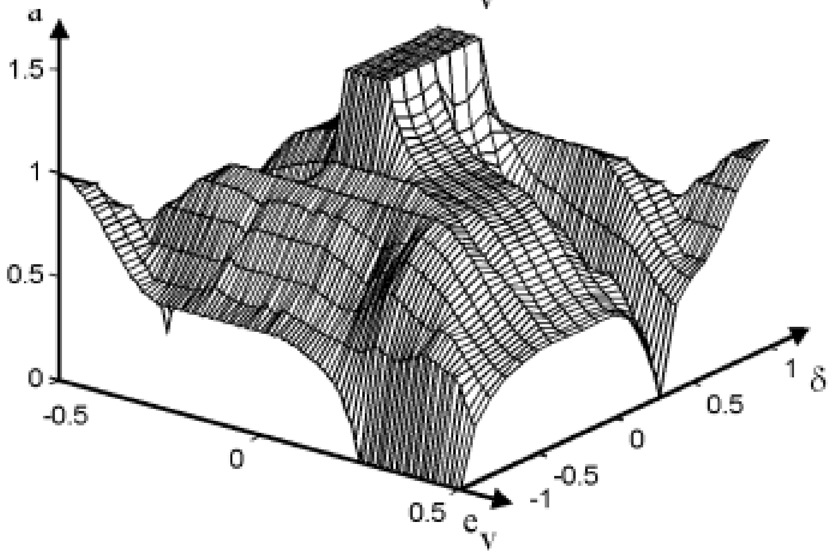
Path tracking of an automated guided vehicle

Control surfaces (Zadeh-Mamdani + COG FLC)

- For the **steering V_d**:

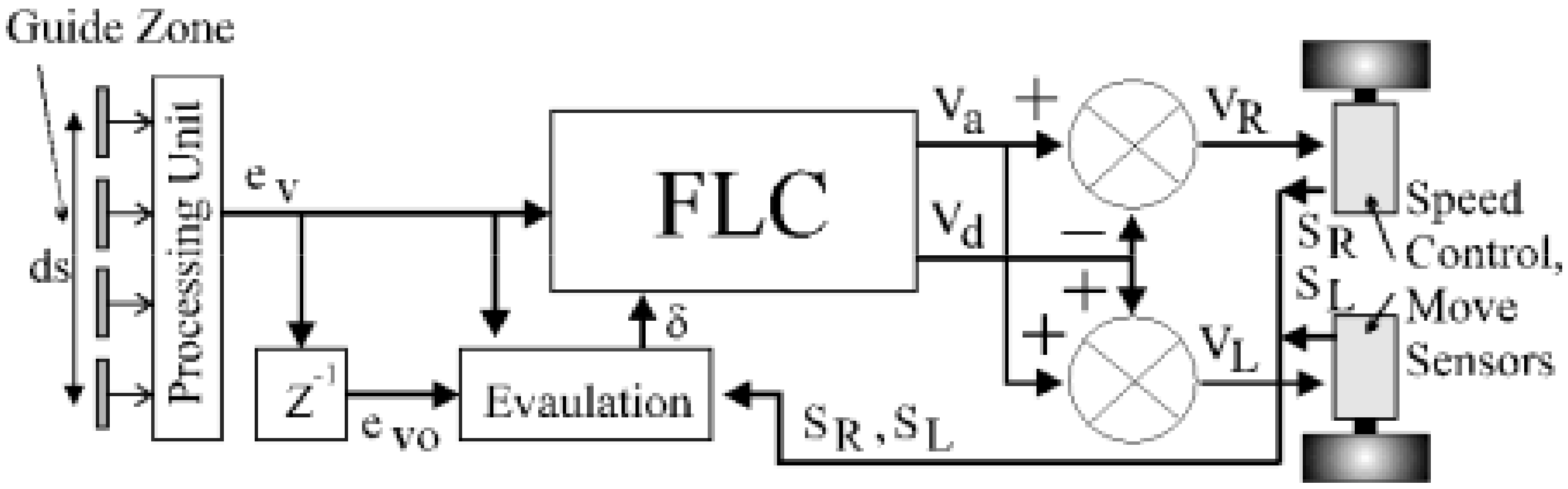


- For the **speed V_a**:



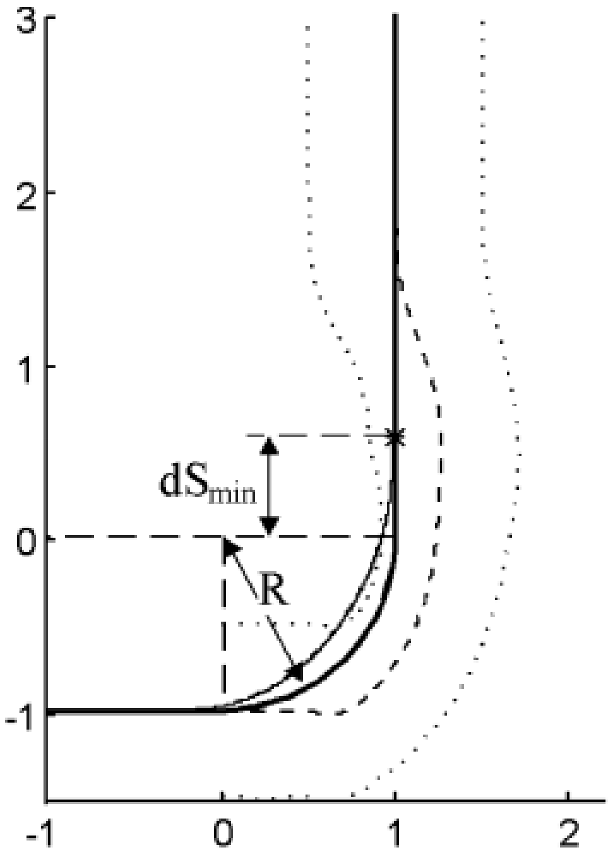
Path tracking of an automated guided vehicle

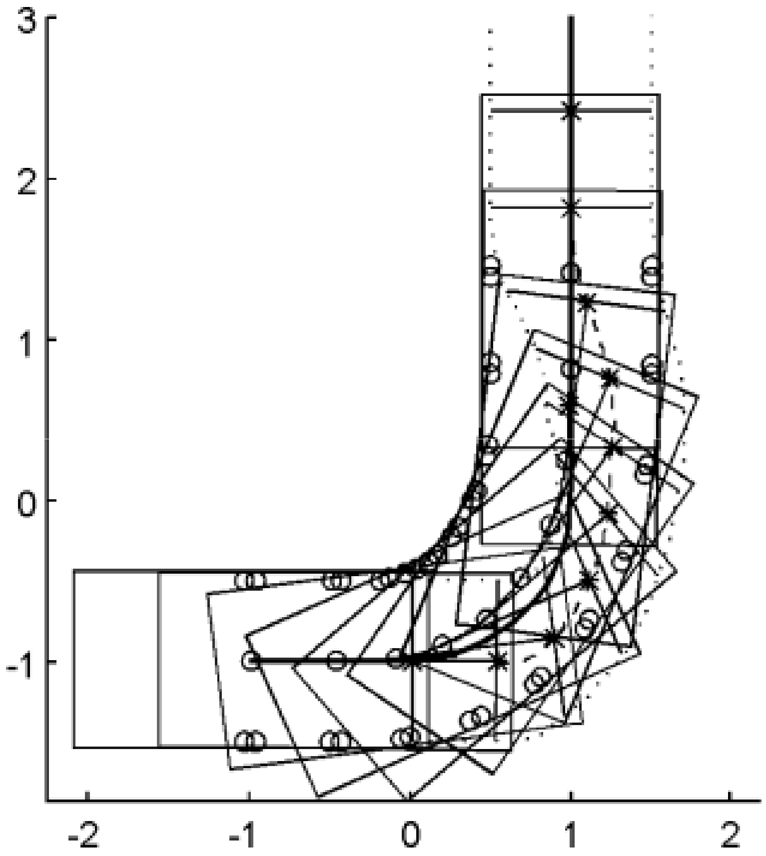
Structure of the guidance system of a differential steered AGV using the guide zone based path tracking strategy



Path tracking of an automated guided vehicle

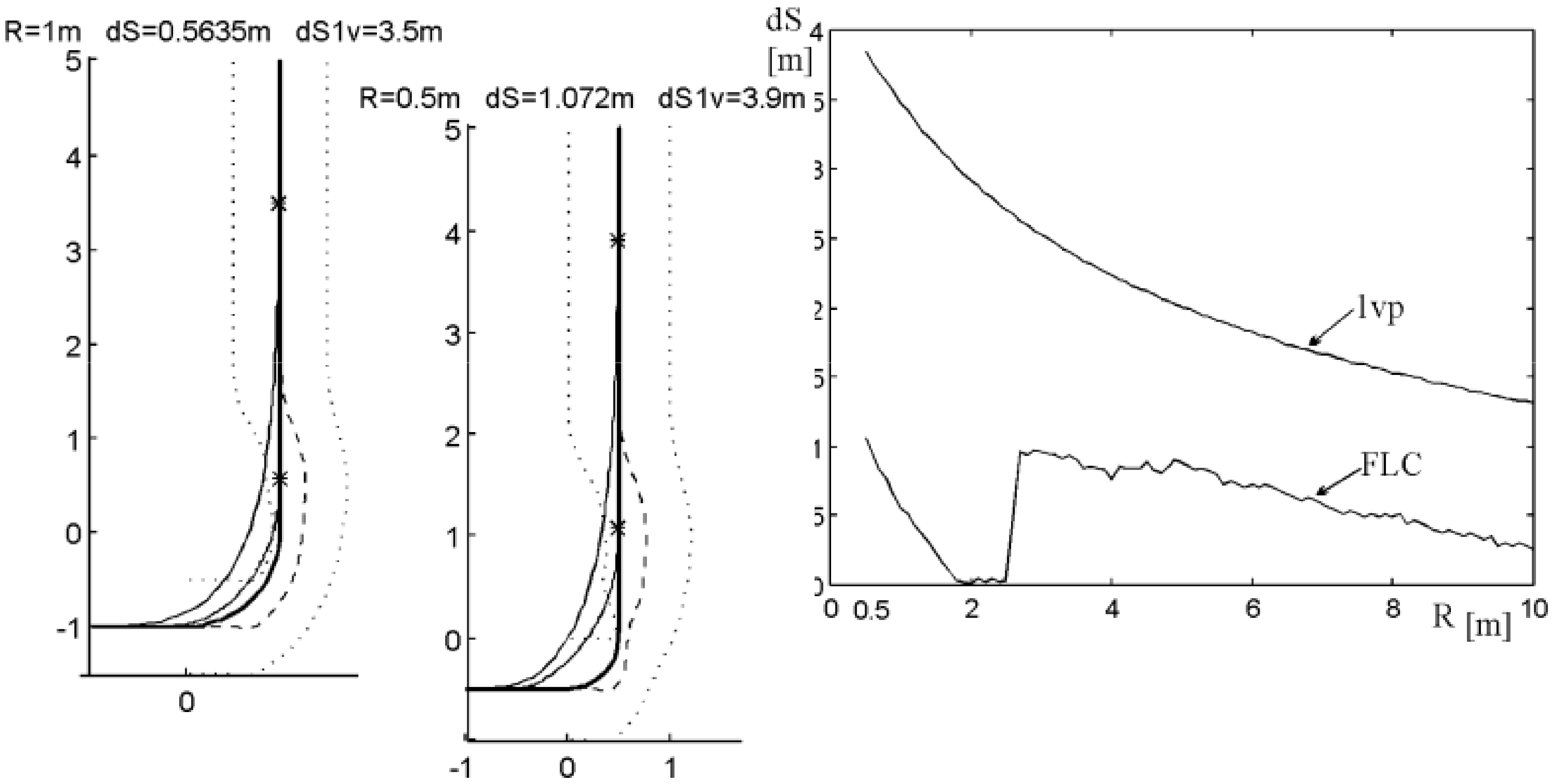
Performance of the fuzzy logic controlled path tracking guidance



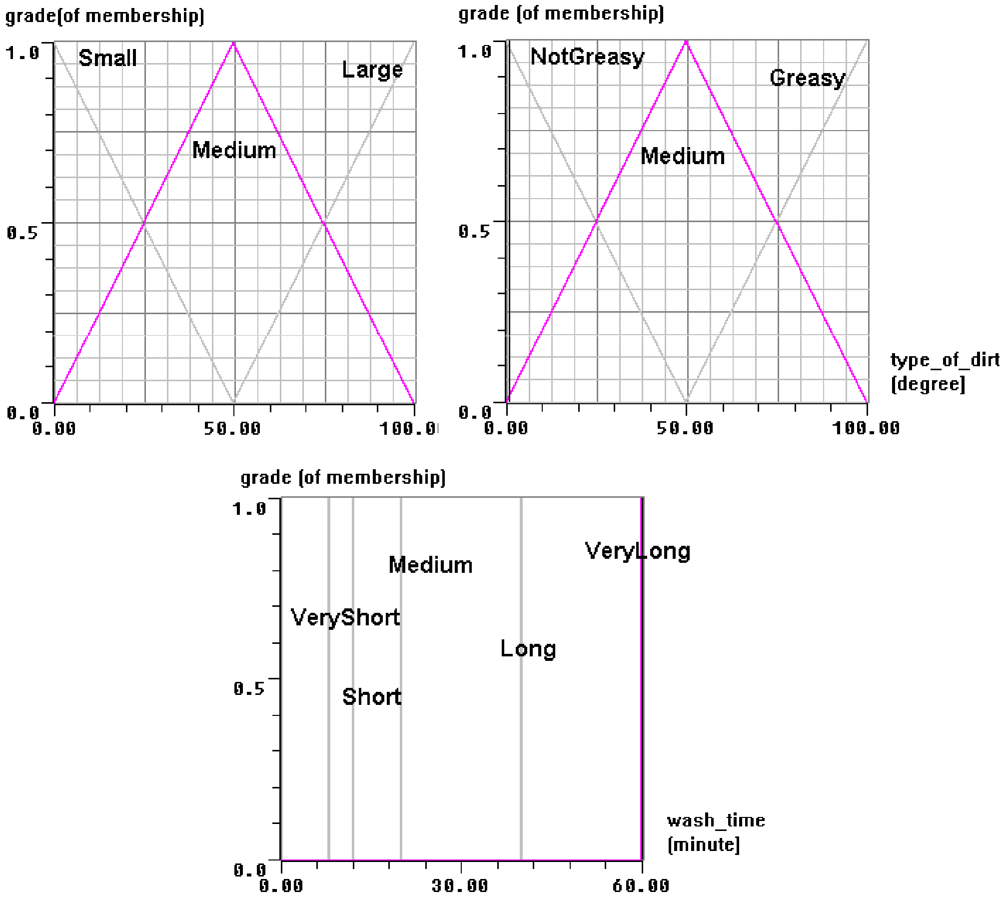


Path tracking of an automated guided vehicle

Performance of the fuzzy logic controlled path tracking guidance with respect to the *minimal docking distance* (dS)



Fuzzy-controlled Washing Machine (Aptronix Examples)



- **Objective**

  Design a washing machine controller, which gives the correct wash time even though a precise model of the input/output relationship is not available

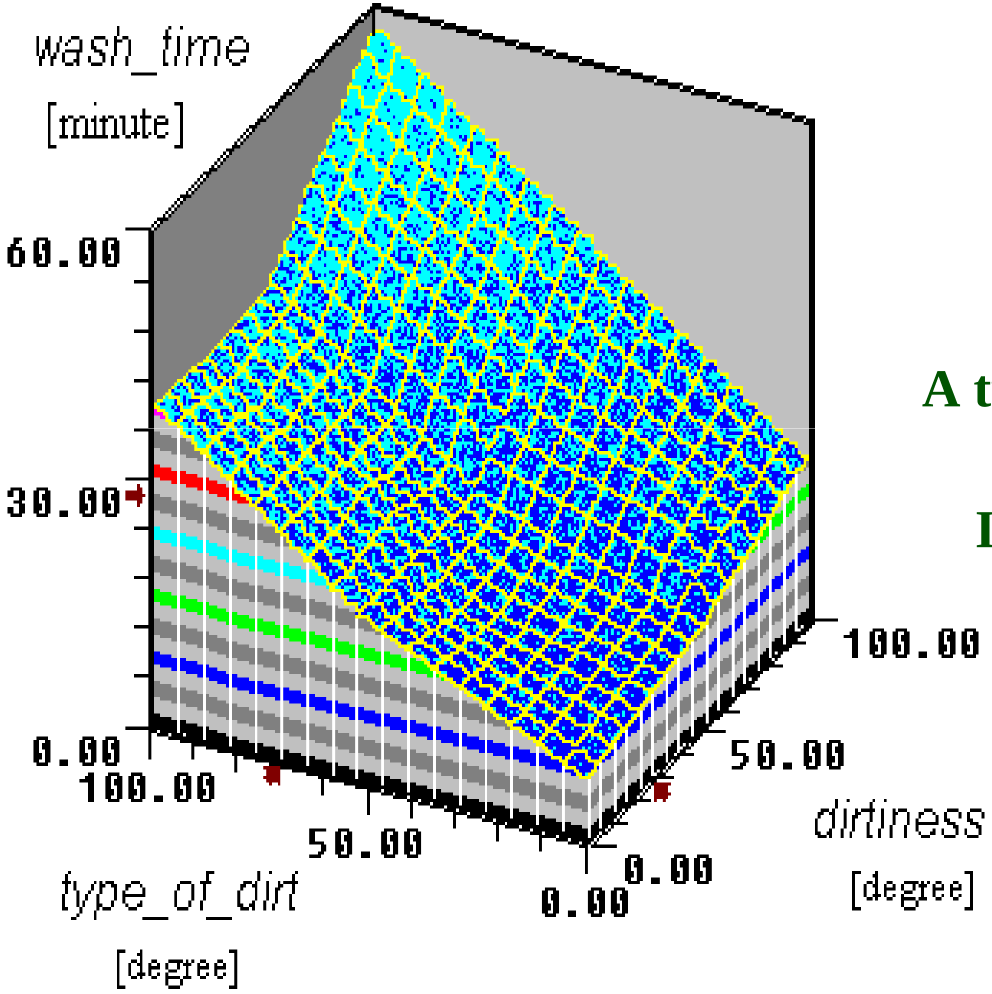
- **Inputs:**

  Dirtyness, type of dirt

- **Output:**

  Wash time

Fuzzy-controlled Washing Machine



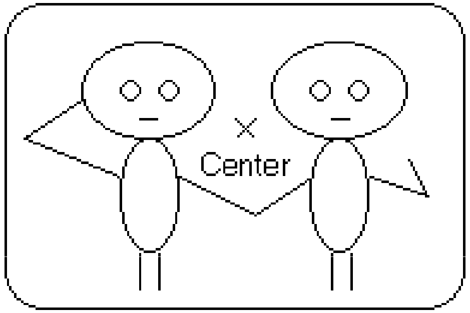
- Rules for our washing machine controller are derived from common sense data taken from typical home use, and experimentation in a controlled environment.

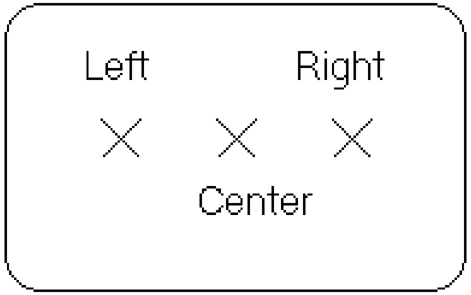
A typical intuitive rule is as follows:

If *saturation time* is long and *transparency* is bad, then *wash time* should be long.

(átitatódási idő, átlátszóság)

Automatic Focusing System





- **Cameras with automatic focusing systems usually measure the distance to the center of a finder's view. This method, however, is inaccurate when the object of interest is not at the center of the view (see fig.).**
- **Approach: Measuring more than one distance + fuzzy inference**

Objective

Determine the object distance using three distance measures for an automatic camera focusing system.

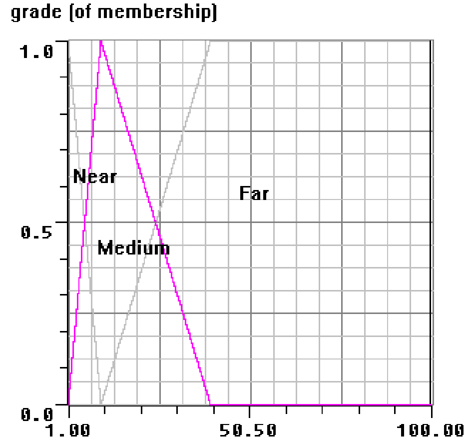
Inputs - the three distance measures at left, center and right points in the finder's view.

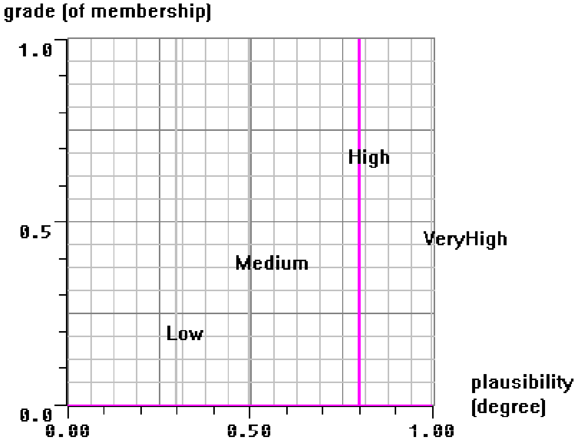
Outputs - the plausibility values associated with these three points.

The point with the highest plausibility is deemed to be the object of interest.

Its distance is then forwarded to the automatic focusing system.

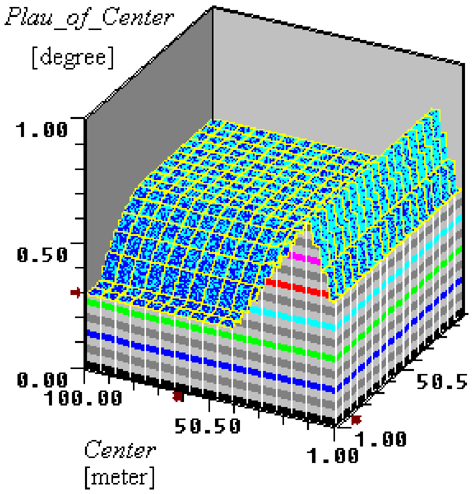
Automatic Focusing System

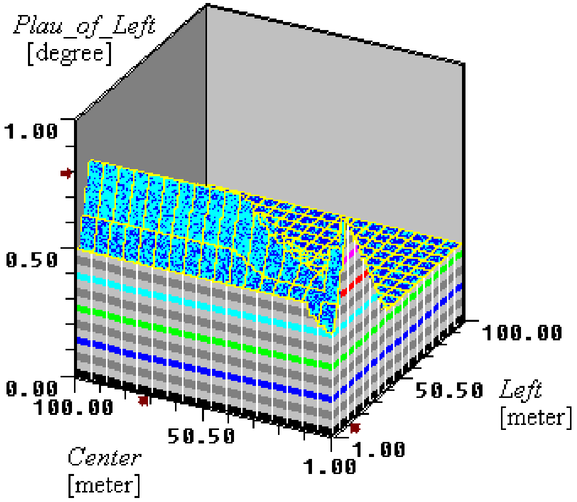




Each input variable, representing distance, has three labels: Near, Medium, and Far.

Each output variable, representing plausibility, has four labels: Low, Medium, High, and VeryHigh





The guiding principle for establishing rules of this automatic focusing system is that the likelihood of an object being at medium distance (typically 10 meters) is high, and becomes very low as distance increases (say, more than 40 meters).

Automatic Focusing System

RULES

if Left is Near then Plau_of_Left is Medium;

if Center is Near then Plau_of_Center is Medium;

if Right is Near then Plau_of_Right is Medium;

if Left is Near and Center is Near and Right is Near then Plau_of_Center is High;

if Left is Near and Center is Near then Plau_of_Left is Low;

if Right is Near and Center is Near then Plau_of_Right is Low;

if Left is Medium then Plau_of_Left is High;

if Center is Medium then Plau_of_Center is High;

if Right is Medium then Plau_of_Right is High;

if Left is Medium and Center is Medium and Right is Medium then Plau_of_Center is VeryHigh;

if Left is Medium and Center is Medium then Plau_of_Left is Low;

if Right is Medium and Center is Medium then Plau_of_Right is Low;

if Left is Far then Plau_of_Left is Low;

if Center is Far then Plau_of_Center is Low;

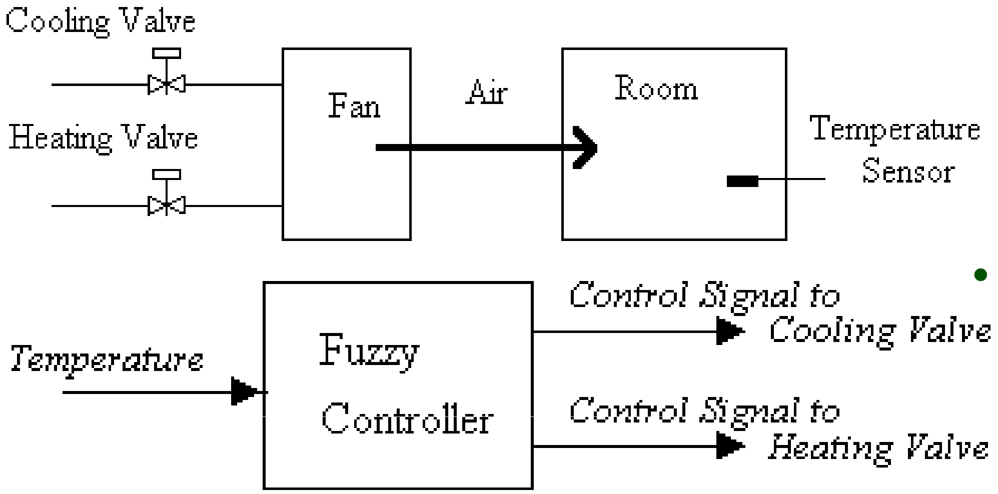
if Right is Far then Plau_of_Right is Low;

if Left is Far and Center is Far and Right is Far then Plau_of_Center is High;

if Left is Medium and Center is Far then Plau_of_Center is Low;

if Right is Medium and Center is Far then Plau_of_Center is Low

Air Conditioning Temperature Control



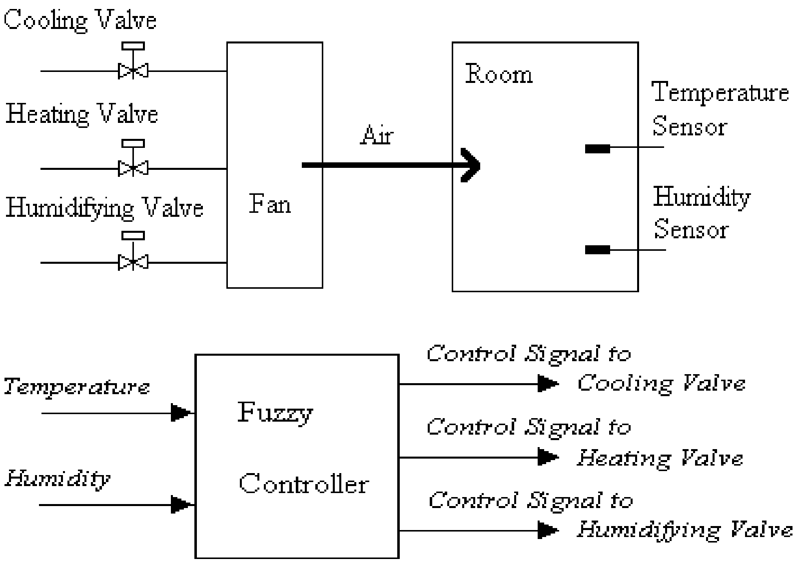
- **There is a sensor in the room to monitor temperature for feedback control, and there are two control elements, cooling valve and heating valve, to adjust the air supply temperature to the room.**

- **Temperature control has several unfavorable features: non-linearity, interference, dead time, and external disturbances, etc.**
- **Conventional approaches usually do not result in satisfactory temperature control.**

Rules for this controller may be formulated using statements similar to:

If ***temperature is*** *low* **then** ***open heating valve*** *greatly*

Air Conditioning Temperature Control – Modified Model



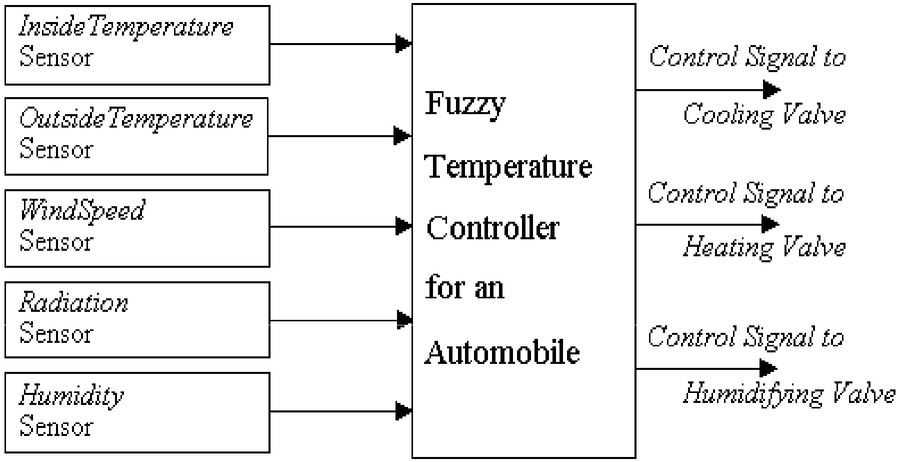
- **There are two sensors in the modified system: one to monitor temperature and one to monitor humidity. There are three control elements: cooling valve, heating valve, and humidifying valve, to adjust temperature and humidity of the air supply.**

Rules for this controller can be formulated by adding rules for humidity control to the basic model.

If temperature is ***low*** *then open humidifying valve* ***slightly.***

This rule acts as a predictor of humidity (it leads the humidity value) and is also designed to prevent overshoot in the output humidity curve.

Advanced Model for Automobile Passenger Environment



Inside Temperature Sensor

Outside Temperature Sensor

Wind Speed Sensor

Radiation Sensor

Humidity Sensor

Fuzzy Temperature Controller for an Automobile

Control Signal to Cooling Valve

Control Signal to Heating Valve

Control Signal to Humidifying Valve

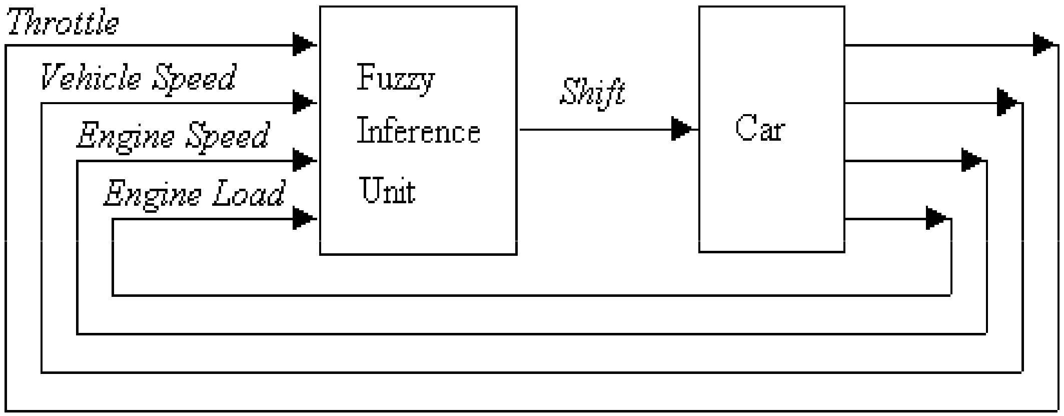
- Controller outperforms conventional control systems substantially.
- It prevents rapid change of temperature in the car when doors or windows are opened and then closed. It even reacts to weather changes - interior humidity changes caused by the weather detected by sensors

- **Temperature control in an automobile passenger environment is more complex than that of a static room. Temperature and humidity should be controlled to provide an enjoyable ride.**
- **Critical to keep windows from being fogged – cause = a temperature differential between inside and outside air in combination with the interior humidity.**
- **To obtain satisfactory control results, the strength of sunshine radiation and the automobile speed must also be factored in.**

Other Automotive Applications of Fuzzy Control

- Antilock brakes
- Servo Motor Force Control
- Transmission Control
- Suspension
- Smart car / Smart highway concepts

Automatic Transmission

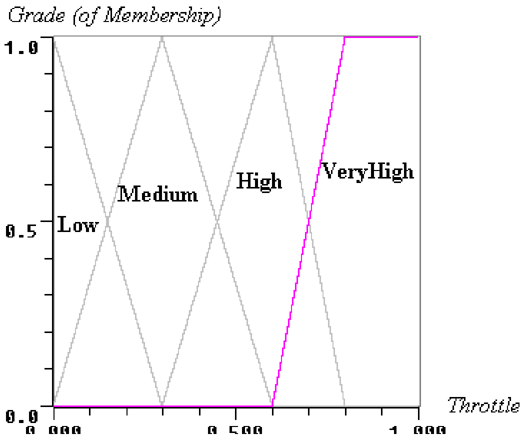


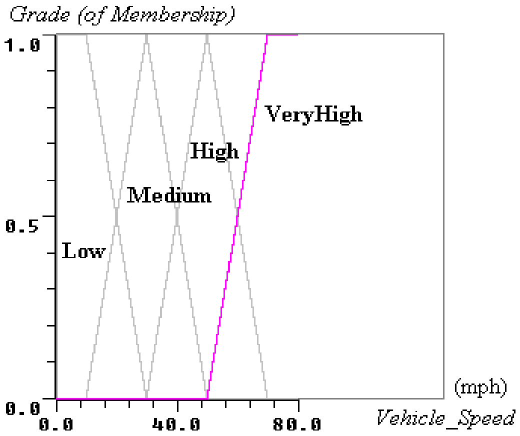
Fuzzy logic is employed to infer the best gear selection. The four fuzzy inference unit inputs are sensor based signals from the car itself.

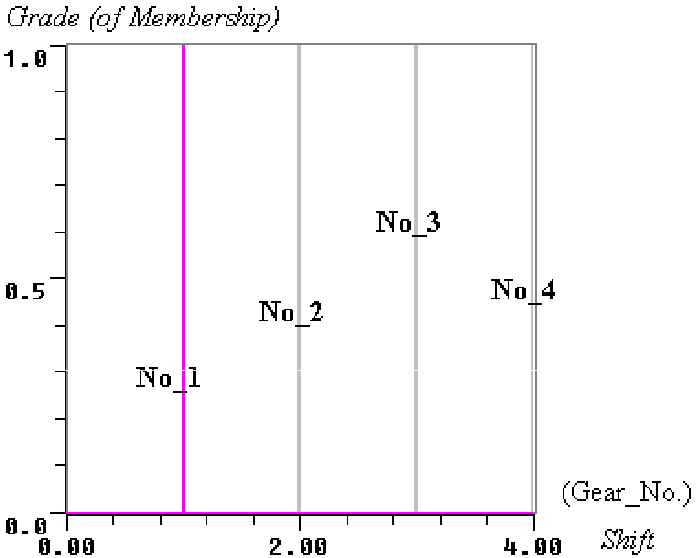
Objective:

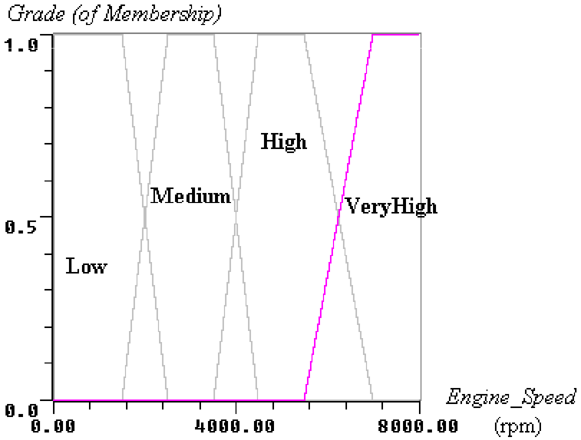
Using *throttle, vehicle speed, engine speed, engine load*, the fuzzy inference unit determines a *shift*, i.e., gear number, for the car.

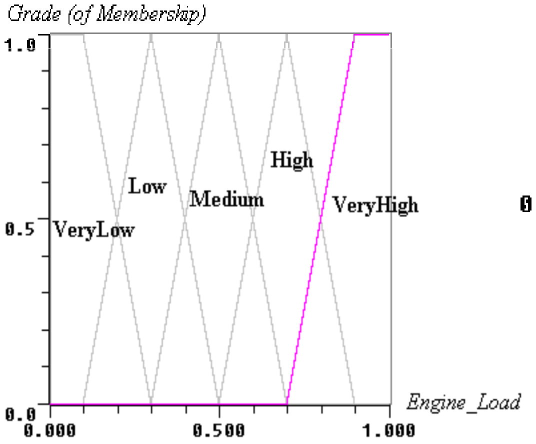
Automatic Transmission



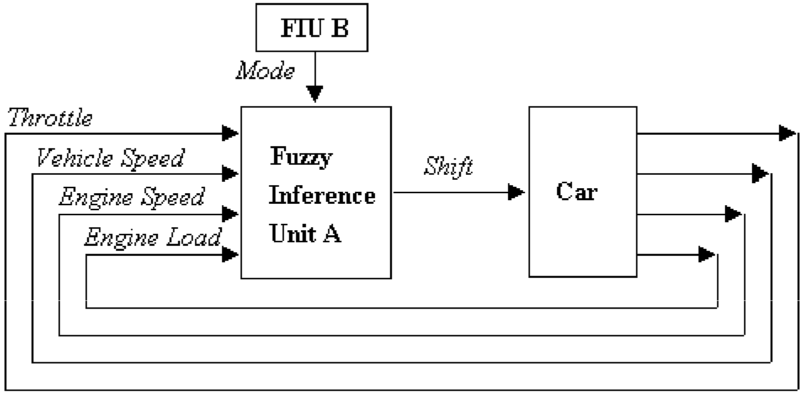


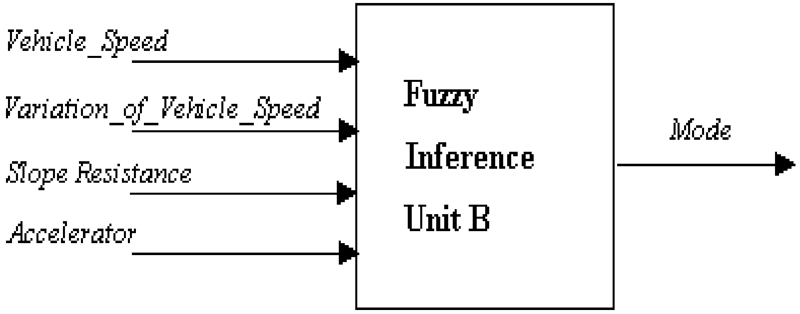






Automatic Transmission – Modified Model





- Performance of the above model is not very good.

  Driving environment not taken into account. Humans, drive in different "modes" depending on road conditions.

  For example, we sometimes drive at a constant low gear when negotiating a windy mountainous road. This avoids unnecessary gear shifting, which can add to engine wear and make for a less than smooth ride for passengers.

  Adding an extra input, *mode*, to the fuzzy inference unit - influences gear shift behavior.

Automatic Transmission – Modified Model

- **If *Vehicle_Speed* is** Low **and *Variation_of_Vehicle_Speed* is** Small **and *Slope_Resistance* is** Positive_Large **and *Accelerator* is** Medium **Then *Mode* is** Steep_Uphill_Mode
- **If *Vehicle_Speed* is** Medium **and *Variation_of_Vehicle_Speed* is** Small **and *Slope_Resistance* is** Negative_Large **and *Accelerator* is** Small **Then *Mode* is** Gentle_Downhill_Mode

- **The driving *mode* output of FIU B can then be further used to affect the gear shifting procedure.**
- **For example, if mode is Steep_Uphill_Mode, a downshift is necessary in order to obtain greater engine power.**
- **If mode is Gentle_Downhill_Mode, we also need a lower gear than would be the case for a flat smooth road. The lower gear provides engine braking power. Typical gear selection rules could look as follows:**

- **If *Mode* is** Steep_Uphill_Mode **then *Shift* is** No_2
- **If *Mode* is** Gentle_Downhill_Mode **then *Shift* is** No_3

Platoons of Smart Cars

Platoons

= high speed groups of smart cars in single lanes.

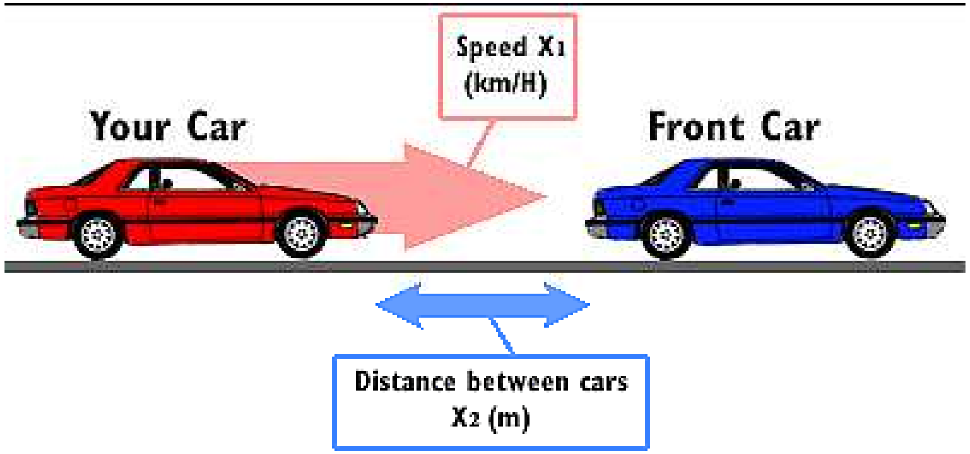
- The lead car plans the course of the platoon – picks the velocity, car spacing, maneuvers to perform
- Increase the throughput of the highways

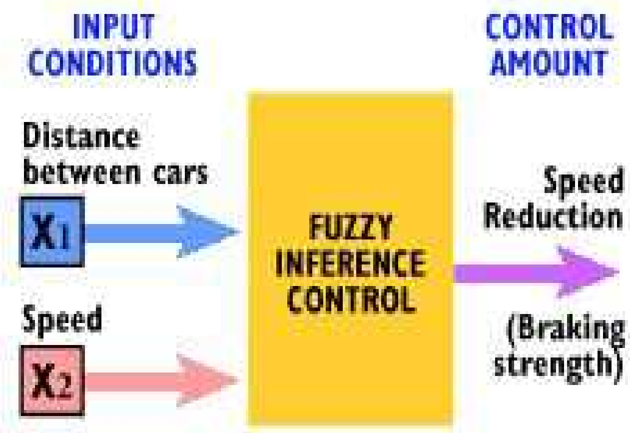
- The fuzzy platoon controller (FPC) = distributed control system for future freeways that drive a car in or out of a platoon.
- The FPC includes an integrated maneuver controller (IMC) for course selection and an individual vehicle controller (IVC) for throttle, brake and steering control.
- Course selection in IMC involves merge, split, velocity change and lane change.

Fuzzy throttle controller for velocity and gap control.

The controller gets information from its own sensors, the car ahead, and from the platoon goals.

Fuzzy Control of Platoons of Smart Cars





Platoon of Smart Cars 1 - Rules

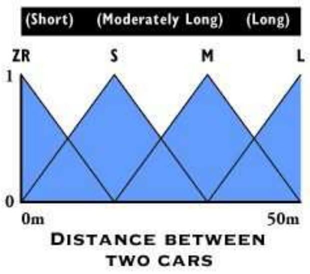
The number of rules depends on the problem.

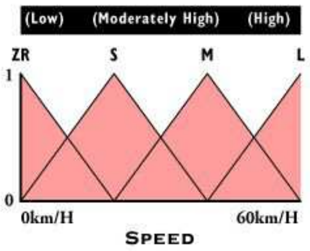
We shall consider only two for the simplicity of the example:

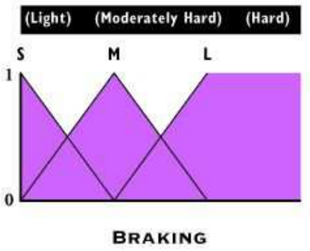
Rule 1: If the distance between two cars is short and the speed of your car is high(er than the other one’s), then brake hard.

Rule 2: If the distance between two cars is moderately long and the speed of your car is high(er than the other one’s), then brake moderately hard.

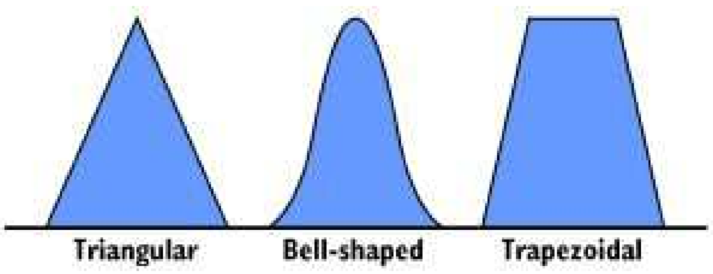
Platoon of Smart Cars 2 – Membership Functions



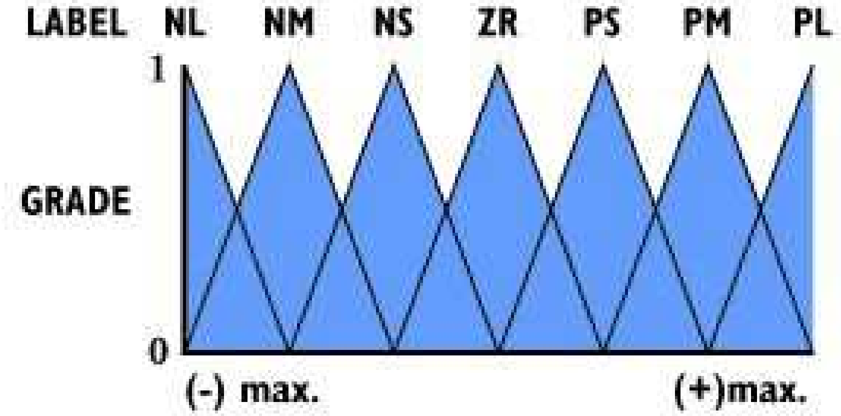




- **Determine the membership functions for the antecedent and consequent blocks**
- **Most frequently 3, 5 or 7 fuzzy sets are used (3 for crude control, 5 and 7 for finer control results)**
- **Typical shapes (triangular – most frequent)**



Platton of Smart Cars 3 – Simplify Rules using Codes



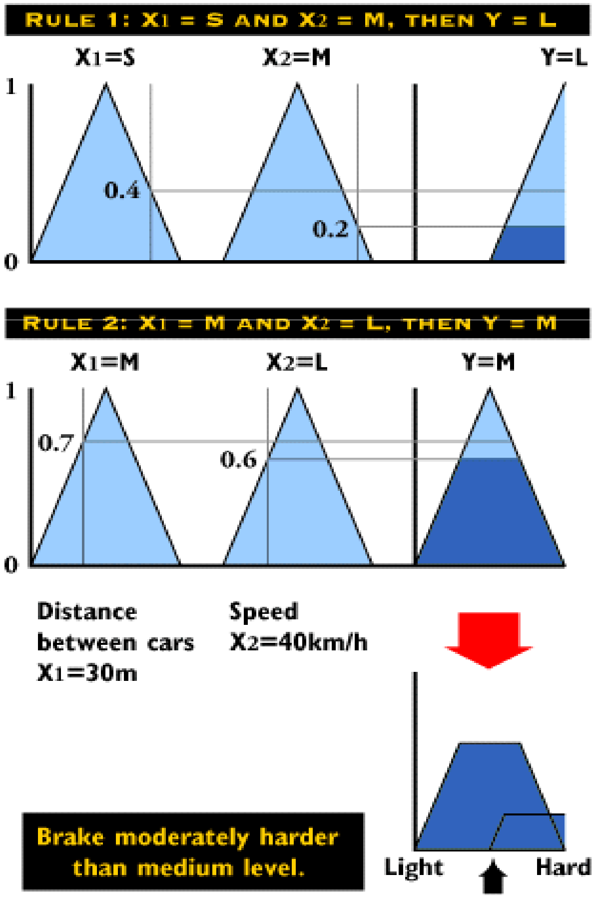
PL - Positive Large
PM - Positive Medium
PS - Positive Small
ZR - Aproximately Zero
NS - Negative Small
NM - Negative Medium
NL - Negative Large

- Distance between two cars: X1
  speed: X2
  Breaking strength: Y
  Labels- small, medium, large: S, M, L
- In the case of X2 (speed), small, medium, and large mean the amount that this car's speed is higher than the car in front.
- Rule 1:

  If X1=S and X2=M, then Y=L
  Rule 2:

  If X1=M and X2=L, then Y=M

Platoon of Smart Cars 4 - Inference



- Determine the degree of matching
- Adjust the consequent block
- Total evaluationof the conclusions based on the rules

  To determine the control amount at a certain point, a defuzzifier is used (e.g. the center of gravity).
  In this case the center of gravity is located at a position somewhat harder than medium strength, as indicated by the arrow

Modeling Fuel Injection Control Maps

- Motivation is started to be the need for a development tool for automatic calibration of the engine management systems.
- In the past look up tables for fuel injection control of engines could be obtained at the engine test bed using a trial and error method.
- The engine developer constructs a three dimensional map stationary engine operation and subsequently augments these maps with changing operation conditions (acceleration, warm-up, etc.)
- In practice this worked well with simple gasoline engines.
- Sequential carburetors, variable manifolds, as well as emission regulations have made this trial and error approach much harder and impractical.
- A development tool for transferring the developer’s expertise into an automated system is needed.

Modeling Fuel Injection Control Maps

- The initial neural network phase tests the relevance of input parameters to the performance of the system.
- Initially, all inputs are used in the training of a three layer feedforward neural network.
- After the first training is complete, a single input value is varied and the results are observed.
- If the change in the output is negligible, the selected input is deemed to be unimportant and is discarded (sensitivity analysis).
- This procedure identified that the relevant inputs were engine speed and inlet manifold pressure.
- Throttle opening angle did not affect the representation.
- After identification of the relevant inputs a rule generation process reminiscent of neural network training was used.
- This process identified 65 AND type rules.

Fuzzy Logic Controller for Lateral Vehicle Control

- **Successfully implemented on a full-sized test vehicle(Toyota Celica). The FLC design includes a** feedback module **to infer control action from state errors, a** preview module **to infer control action with respect to preview information regarding upcoming road curvature, and** gain scheduling module **to handle the effects of the velocity of the vehicle. All three strategies are implemented on the test vehicle, automatically following a multiple curved track using discrete magnetic markers on the roadway and magnetometers on the vehicle as a lateral error reference sensing system.**
- **The use of preview information was determined to be vital for acceptable performance.**
- **A comparison is made to similar tests conducted using the frequency shaped linear quadratic controller as well as a PID controller.**

Advantages of Fuzzy Controllers

- Control design process is simpler
- Design complexity reduced, without need for complex mathematical analysis
- Code easier to write, allows detailed simulations
- More robust, as tests with weight changes demonstrate
- Development period reduced

Ajánlott irodalom

- **The slides of this lecture are partially based on the books:**

Kóczy T. László és Tikk Domonkos: ***Fuzzy rendszerek*****,** Typotex Kiadó, 2000, **ISBN 963-9132-55-1**

J.-S. R. Jang, C.-T. Sun, E. Mizutani: ***Neuro-Fuzzy and Soft Computing*****,** Prentice Hall, 1997, **ISBN 0-13-261066-3**

Michael Negnevitsky: ***Artificial Intelligence: A Guide to Intelligent Systems*****,** Addison Wesley, Pearson Education Limited, 2002, **ISBN 0201-71159-1**