The Guide Path Controlled AGV
(Automatically Guided Vehicle)

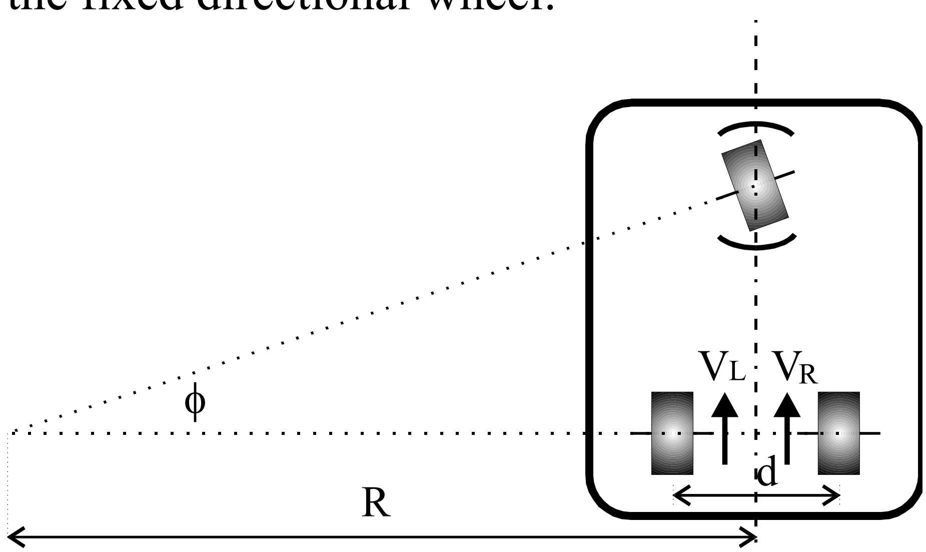
The guide path: a painted marking, or a passive or active wire (guidewire) glued onto or build into the floor.

The goal of the steering: to follow the marking of the guide path.

The number of the guide path sensors: depends on the wheel configuration. The AGVs without fixed directional wheels in their wheel configuration (can be moved to arbitrary direction) usually have two guide path sensors, the AGVs with **at least one fixed directional wheel have only one**.

The guide point: is a point of the AGV determined by the **guide path sensor**. The **goal of the steering control** is to **follow the guide path with the guide point**.

An AGVs **with at least one fixed directional wheel** can run only on a path curve has its momentary centre on the line fits the axe of the fixed directional wheel:



$$R = d \cdot \frac{V_R + V_L}{2 \cdot \left(V_R - V_L\right)}$$

Problem of the guide point based path tracking strategy: the path tracking error (the distance of the guide path and the driving centre of the AGV) **decreasing relatively slow:**

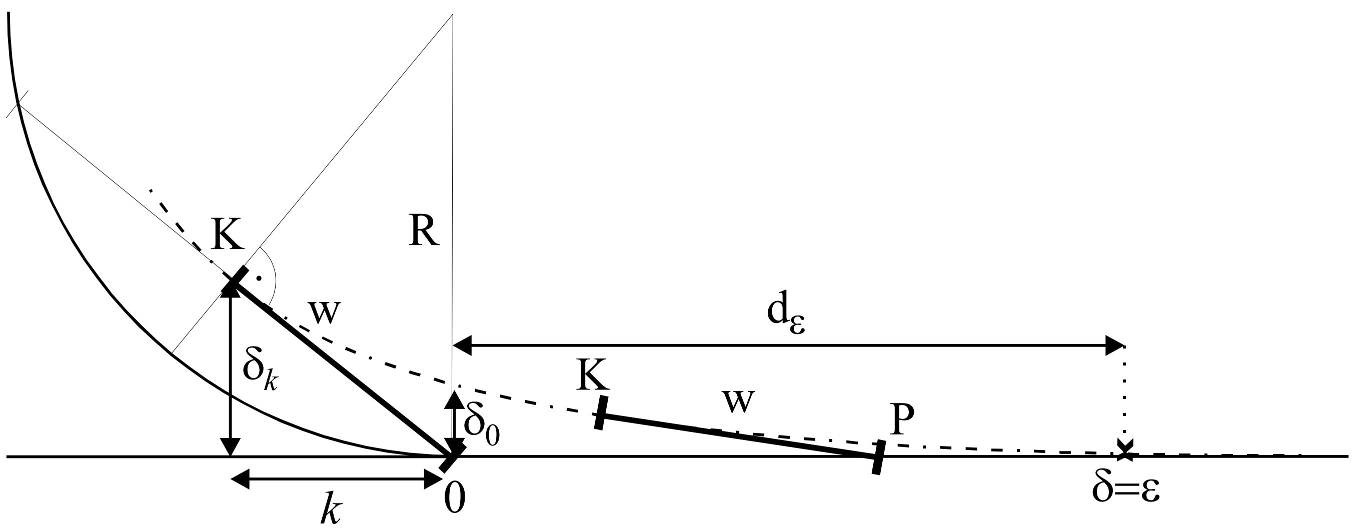
$$d(\delta) = k(\delta_0) - w \cdot \ln\left(\frac{\sqrt{w^2 - \delta^2} - w}{\delta}\right) - \sqrt{w^2 - \delta^2},$$

where, $d(\delta)$ is the distance for δ path tracking error,

$k(\delta_0) = w \cdot \ln\left(\frac{\sqrt{w^2 - \delta_0^2} - w}{\delta_0}\right) + \sqrt{w^2 - \delta_0^2}$ constant,

describing the initial path tracking error δ_0,

w is the distance of the guide point and the driving centre of the AGV.

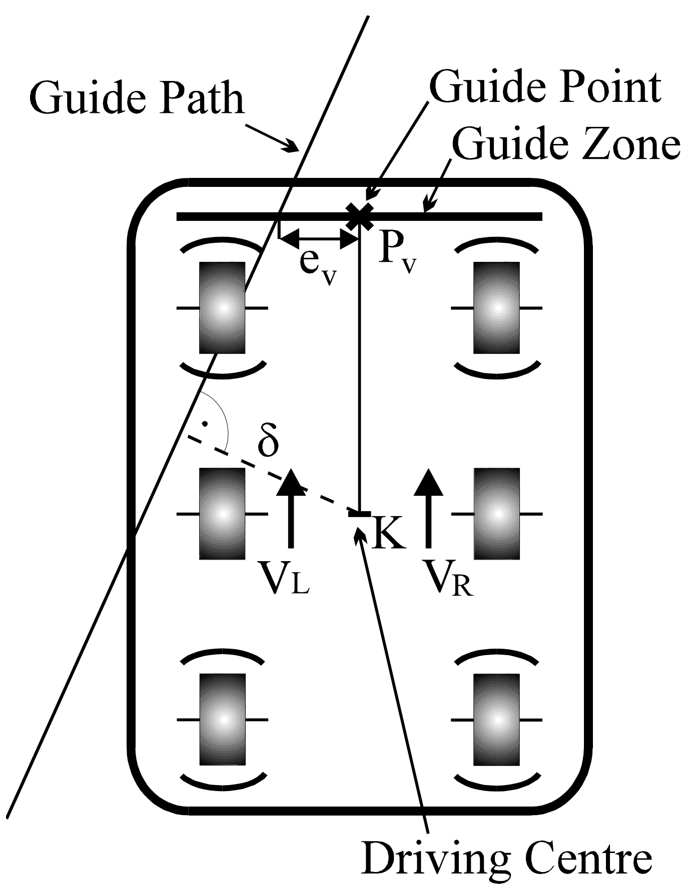


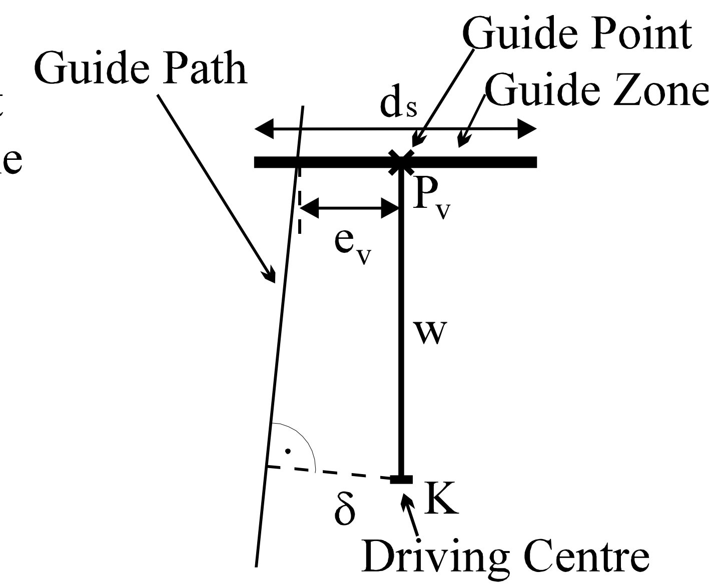
Trajectory of the driving centre of a differential steered AGV using the guide point based path tracking strategy

The **quick convergence** of the trajectory of the driving centre to the guide path is very **important in determining the possible positions of the docking points of the AGV**. Quicker the convergence, quicker the docking accuracy specified for the docking point can be reached, so the minimal distance needed between the last curve of the guide path and a docking point **(minimal docking distance) is shorter** too.

Using the **concept of guide point** based path tracking strategy gives no freedom for the guidance system in choosing trajectory. So we suggest to use the concept of **guide zone**.

The guide zone: is an **extension of the guide point**. It is a section of the AGV determined by the guide path sensor (or raw of sensors). The **goal of the steering** control is to **follow the guide path by the guide zone with minimal path tracking error** on the whole path. This case the guide point is a reference point on the guide zone, indicating the required position of the guide path during docking to the station.
Using the concept of guide zone, the **signal of the guide path sensor is interpreted as a distance** between the guide path and the guide point, instead of the meaning of an error value.





δ	path tracking error
e_v	distance of the guide path, guide point
d_s	width of the guide zone
w	distance of the guide point, driving centre

Differential steered AGV with guide zone

The Path Tracking Control Strategy

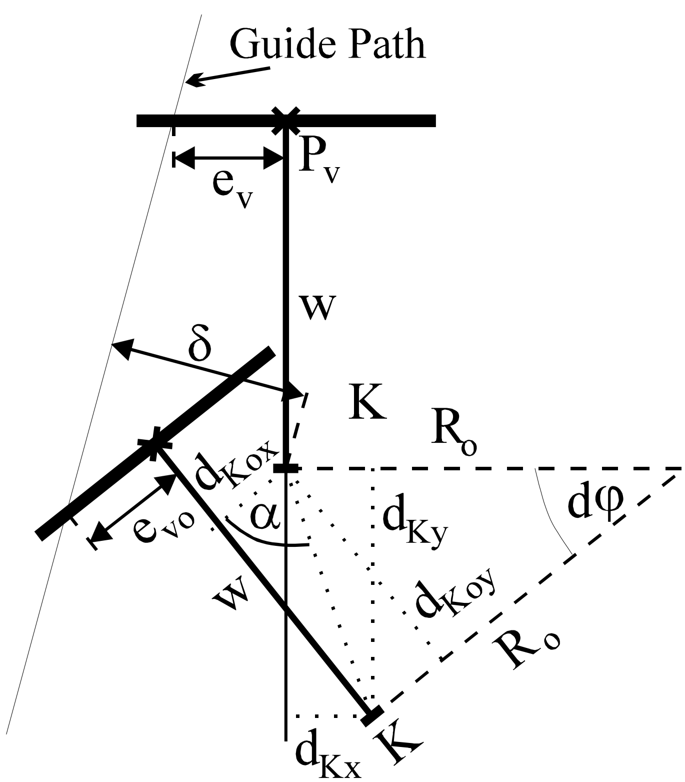
The simplest way of defining a path tracking strategy is based on **collecting the operator's knowledge**.

The guidance strategy: keep the driving centre of the AGV as close as it possible to the guide path, than if the driving centre is close enough to the guide path, simply turn the AGV into the docking direction.

This strategy needs only **two observations**:

- distance between the guide path and the driving centre (**path tracking error** δ),
- **distance between the guide path and the guide point** (e_v can be determined using the **guide zone**).

We suggest to calculate the **estimated momentary path tracking error** from the previous (e_{vo}) and the current value (e_v) of the distance between the guide path and the guide point (measured by the guide zone) and from the move of the AGV.



e_v	distance of the guide path, guide point
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,
d	distance of the two wheels,
d_s	width of the guide zone
w	distance of the guide point, driving centre
δ	the estimated momentary path tracking error.

Rules describing the momentary manoeuvres (steering V_d, speed V_a) **needed for the minimal docking distance** in some significant starting position of the AGV:

$\mathbf{R_{Vd}}$: $e_v =$

$\delta =$	*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***

$\mathbf{R_{Va}}$: $e_v =$

$\delta =$	*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***

Where the i^{th} rules have the following form:

$R_{Vd,i}$ (rules of the steering):

If $e_v = A_{1,i}$ **And** $\delta = A_{2,i}$,

Then $V_d = B_i$.

$R_{Va,i}$ (rules of the speed):

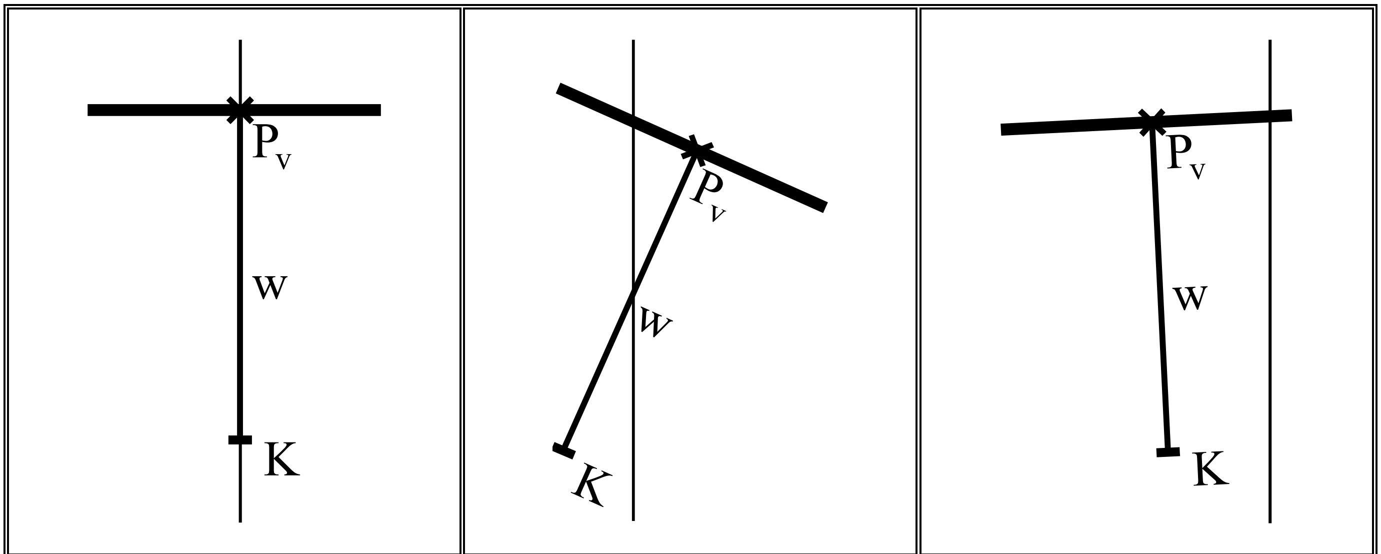
If $e_v = A_{1,i}$ **And** $\delta = A_{2,i}$,

Then $V_a = B_i$.

e.g.,

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

For example:

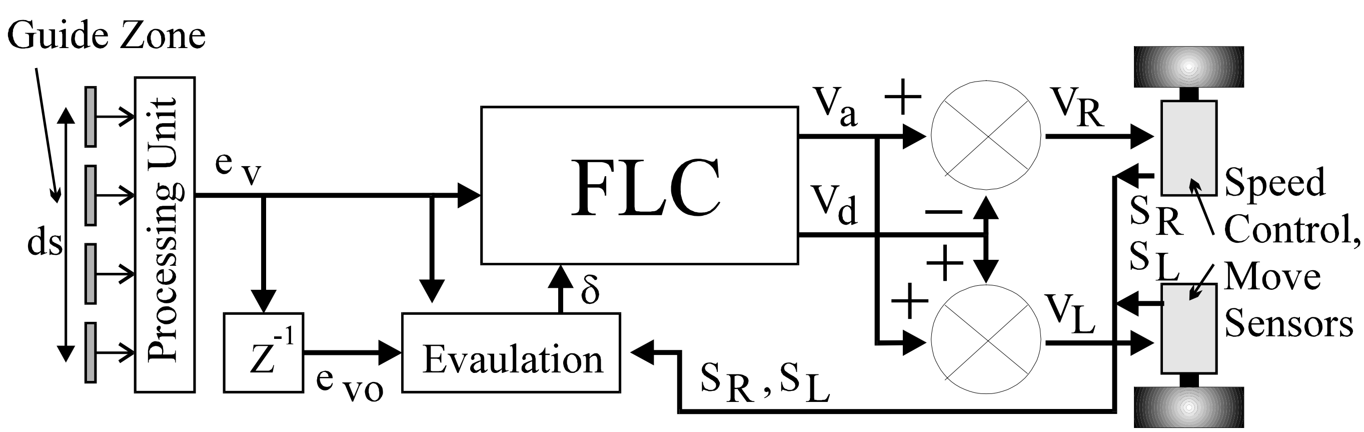


e_v: zero δ: zero	V_d: zero V_a: large	e_v: middle δ: middle	V_d: zero V_a:middle	e_v: large δ:middle	V_d: large→ V_a: small

The AGV we studied has a differential steering, so the speed (V_a) and the steering (V_d) can be calculated as:

$$V_d = V_L - V_R \text{ steering,} \qquad V_a = \frac{V_L + V_R}{2} \text{ speed.}$$

where V_L, V_R is the contour speed of the left and right wheel.

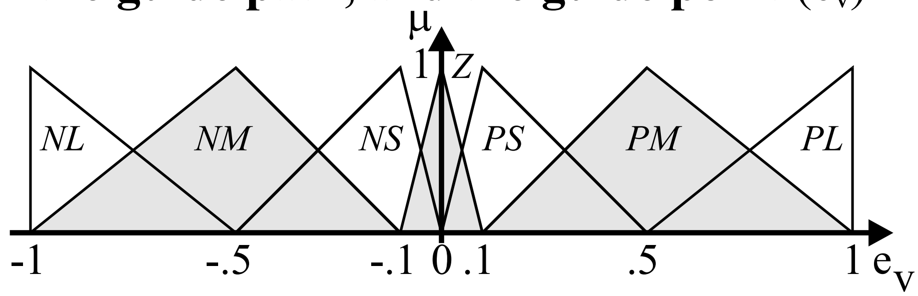


Structure of the guidance system of a differential steered AGV

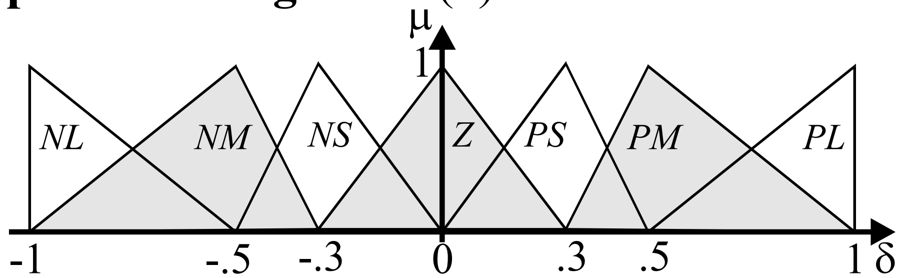
FLC Based on Compositional Rule of Inference

Our rulebases is complete, so we can use the classical **min-max compositional rule of inference** in the fuzzy logic controller.

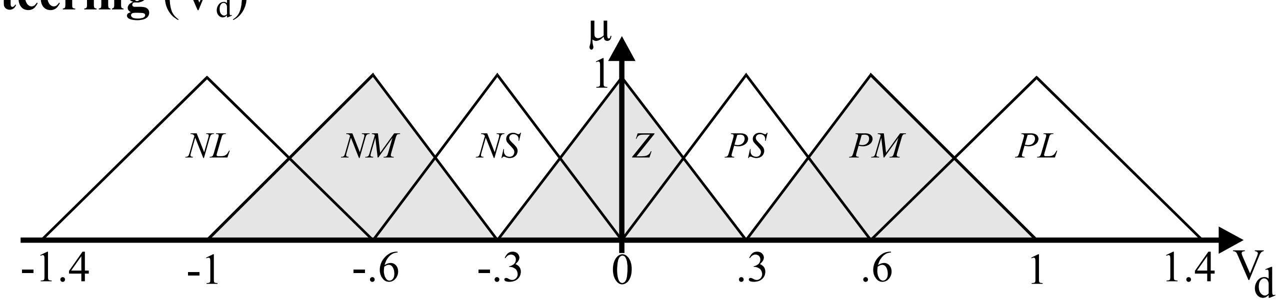
The linguistic terms we have used:
Distance of the guide path, and the guide point (e_v)



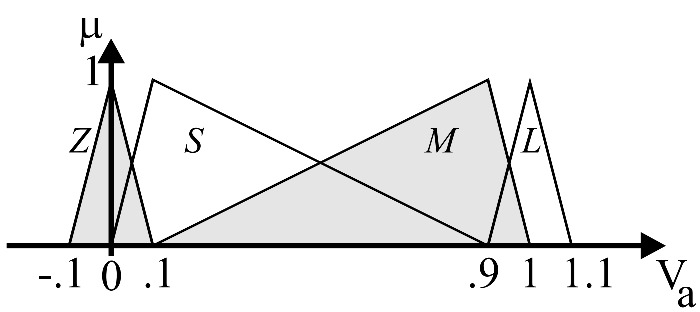
Estimated path tracking error (δ)



Steering (V_d)

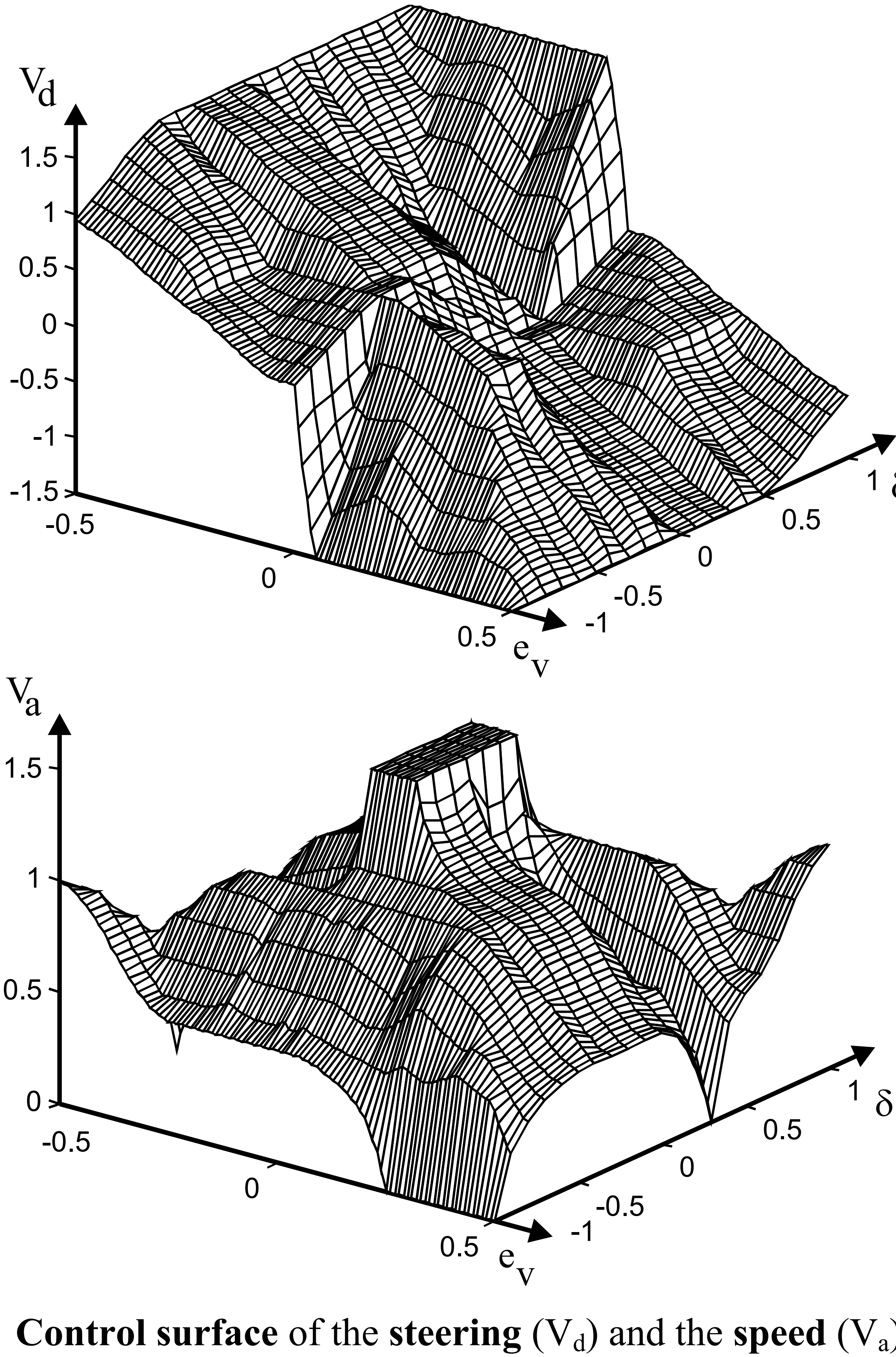


Speed (V_a)



We have generated these fuzzy sets by a tuning process.
The **tuning process was optimized the core positions of the primary fuzzy sets for getting the shortest docking distance** on a trial guide path using a simulated model of an existing AGV.

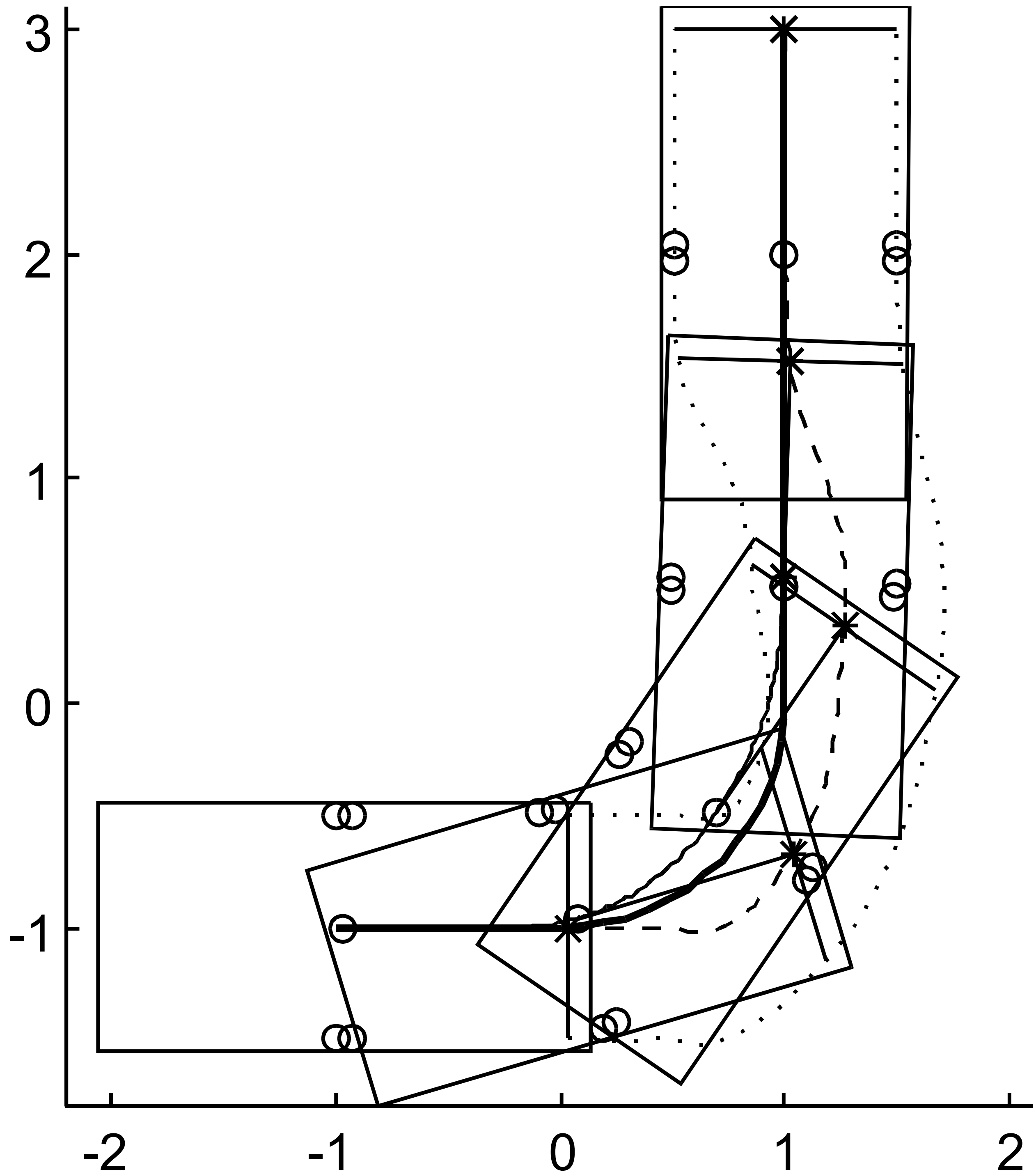
Using the classical method of the **max-min composition** for the **fuzzy rule inference** and the **centre of gravity** method for **defuzzification** we have got the following **control surfaces**:



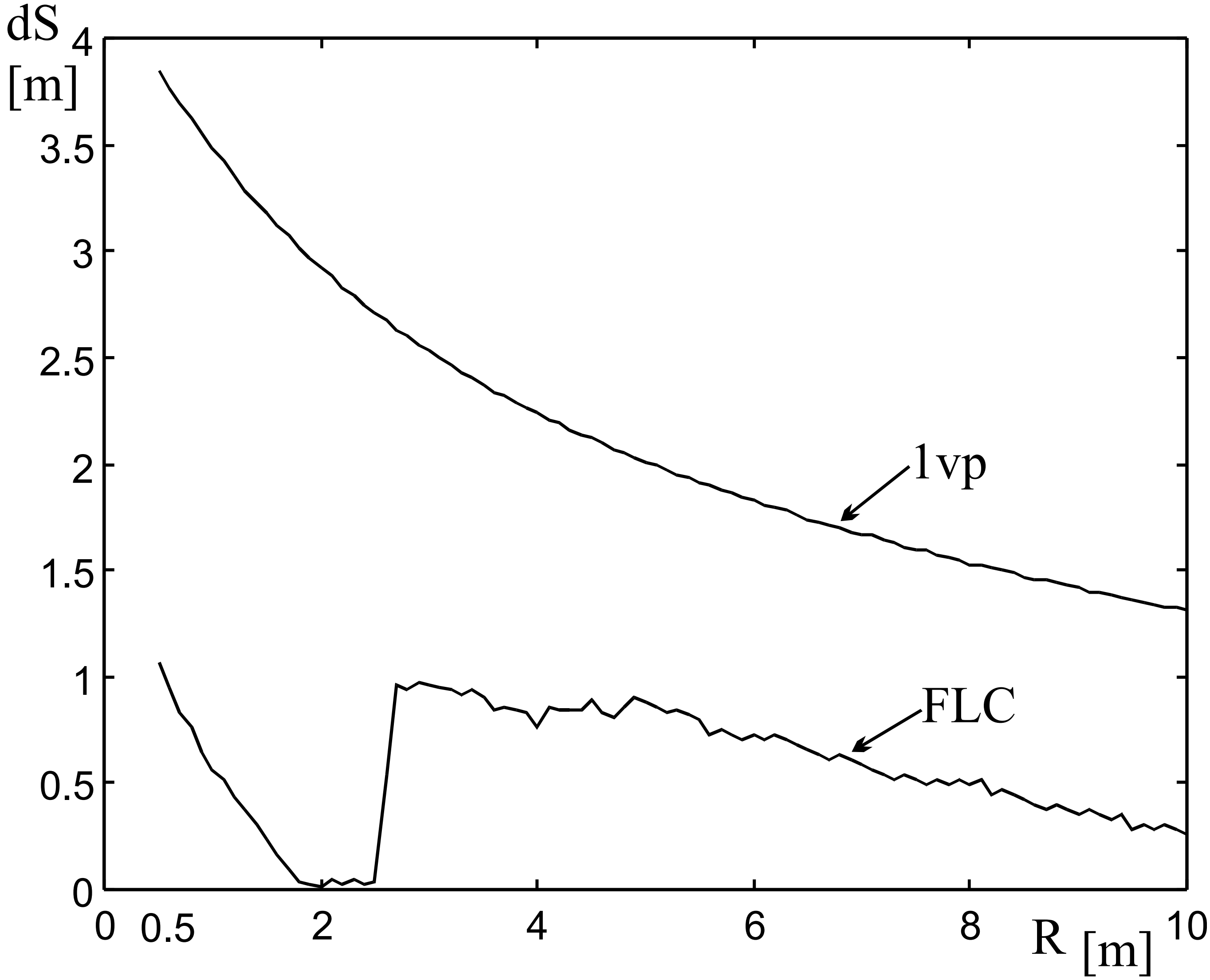
Control surface of the **steering** (V_d) and the **speed** (V_a)

The performance of the CRI based fuzzy logic controller, was **tested on a simulated model of an AGV**.

The **approximated minimal docking distance** of the simulated AGV on a **trial guide path**:



The **approximated minimal docking distances** of the simulated AGV **in function of the guide path radius**:



Minimal docking distances (dS) calculated for the **optimal single guide point based steering system** (1vp) and the simulated results of the AGV using the **CRI based FLC path tracking strategy** (FLC) **in function of the trial guide path radius** (R)

FLC Based on Interpolation in the Vague Environment

For showing the efficiency of the proposed approximate fuzzy reasoning method, **the size of the rulebase**, describing the path tracking strategy, **is reduced dramatically**. All the unimportant rules, rules concluded from the other rules, are removed from the rulebase. It means, that this rulebase contains the most important rules only, so its completeness is necessary.

The reduced rulebase, describing the rules of the momentary steering actions (V_d) **and the momentary speed** (V_a) is the following:

R_{Vd}:

$\delta =$ \ $e_v =$	$NL:$	$NM:$	$Z:$	$PM:$	$PL:$
$NL:$				***NL***	
$NM:$	***PL***		***PS***	***PS***	***NL***
$Z:$		***PL***		***NL***	
$PM:$	***PL***	***NS***	***NS***		***NL***
$PL:$		***PL***			

R_{Va}:

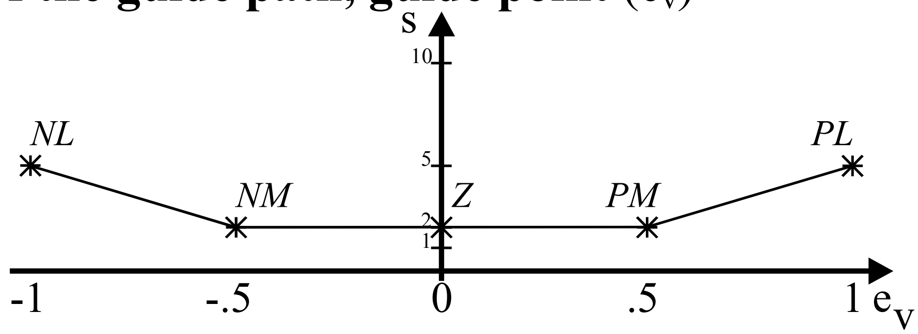
$\delta =$ \ $e_v =$	$NL:$	$NM:$	$Z:$	$PM:$	$PL:$
$NL:$					***Z***
$NM:$					
$Z:$	***S***		***L***		***S***
$PM:$					
$PL:$	***Z***				

Note, that while in the rulebase of the steering (V_d) the conclusion of the rule e_v:zero and δ:zero has no importance (it can be concluded from the surrounding rules), in the rulebase of the speed (V_a) this is one of the most important rules.

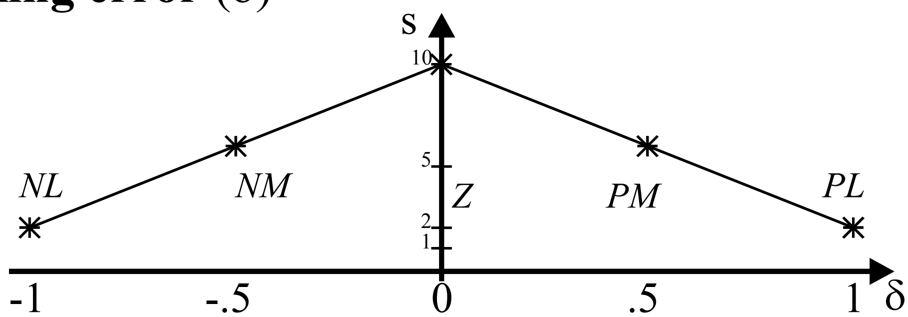
Generating the vague environment of the fuzzy rulebase

For comparing the efficiency of the proposed approximate fuzzy reasoning method to the classical CRI based fuzzy logic controller, **we have applied the same simulated model and environmental parameters for tuning the vague environments** (scaling functions) **and the points of the linguistic variables**.

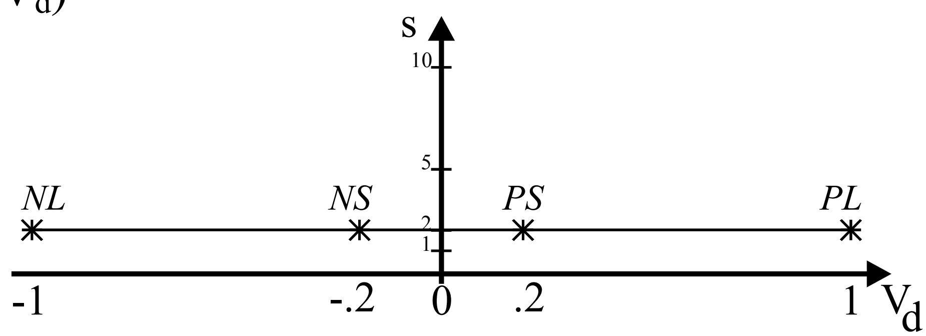
Distance of the guide path, guide point (e_v)



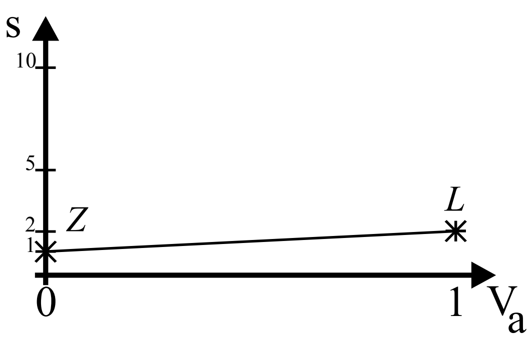
Path tracking error (δ)



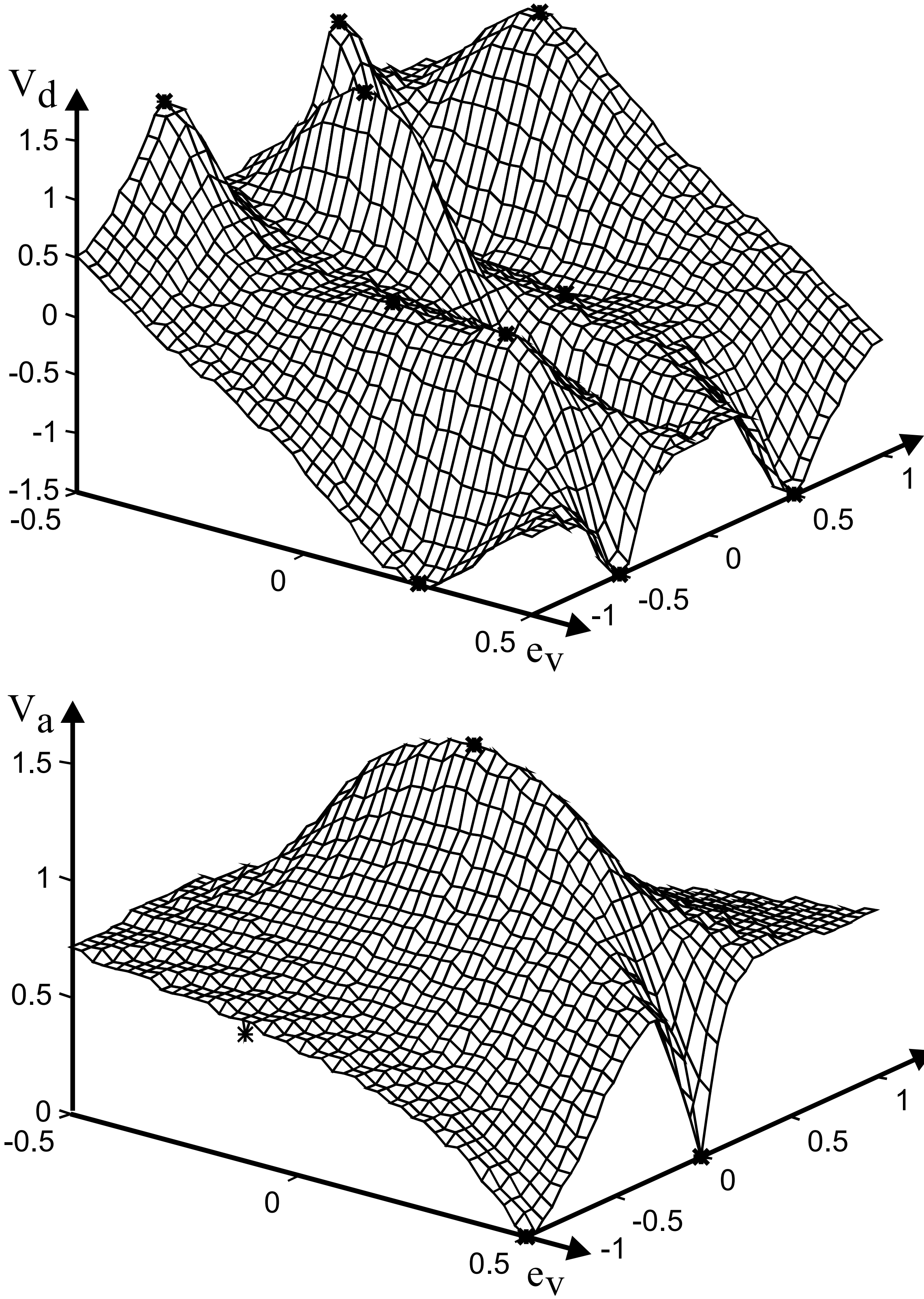
Steering (V_d)



Speed (V_a)

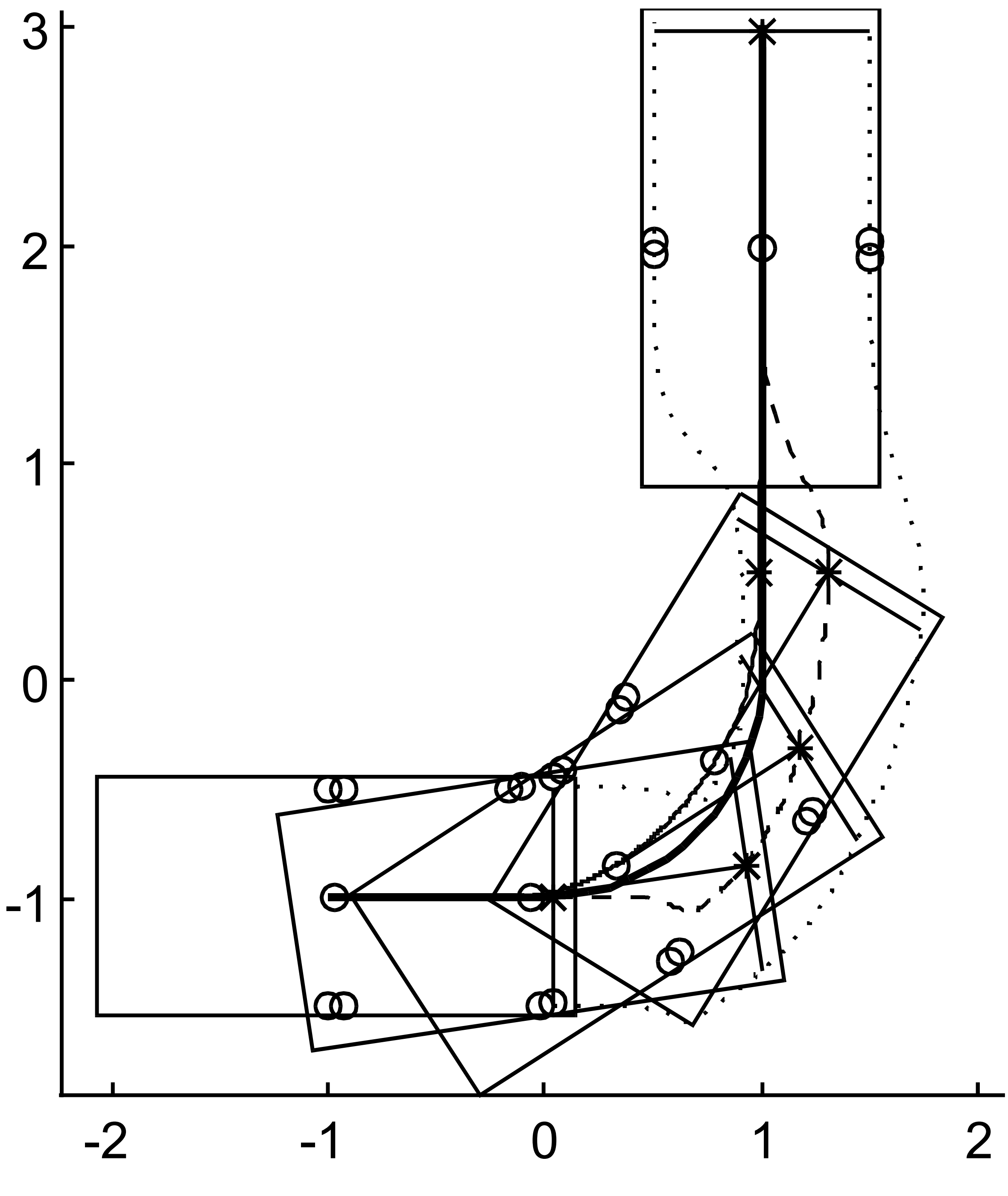


Applying the proposed **approximate fuzzy reasoning method based on rational interpolation** (p=2) we have got the following **control surfaces**:



Control surface of the **steering** (V_d) and the **speed** (V_a)
(the rule points are signed by *)

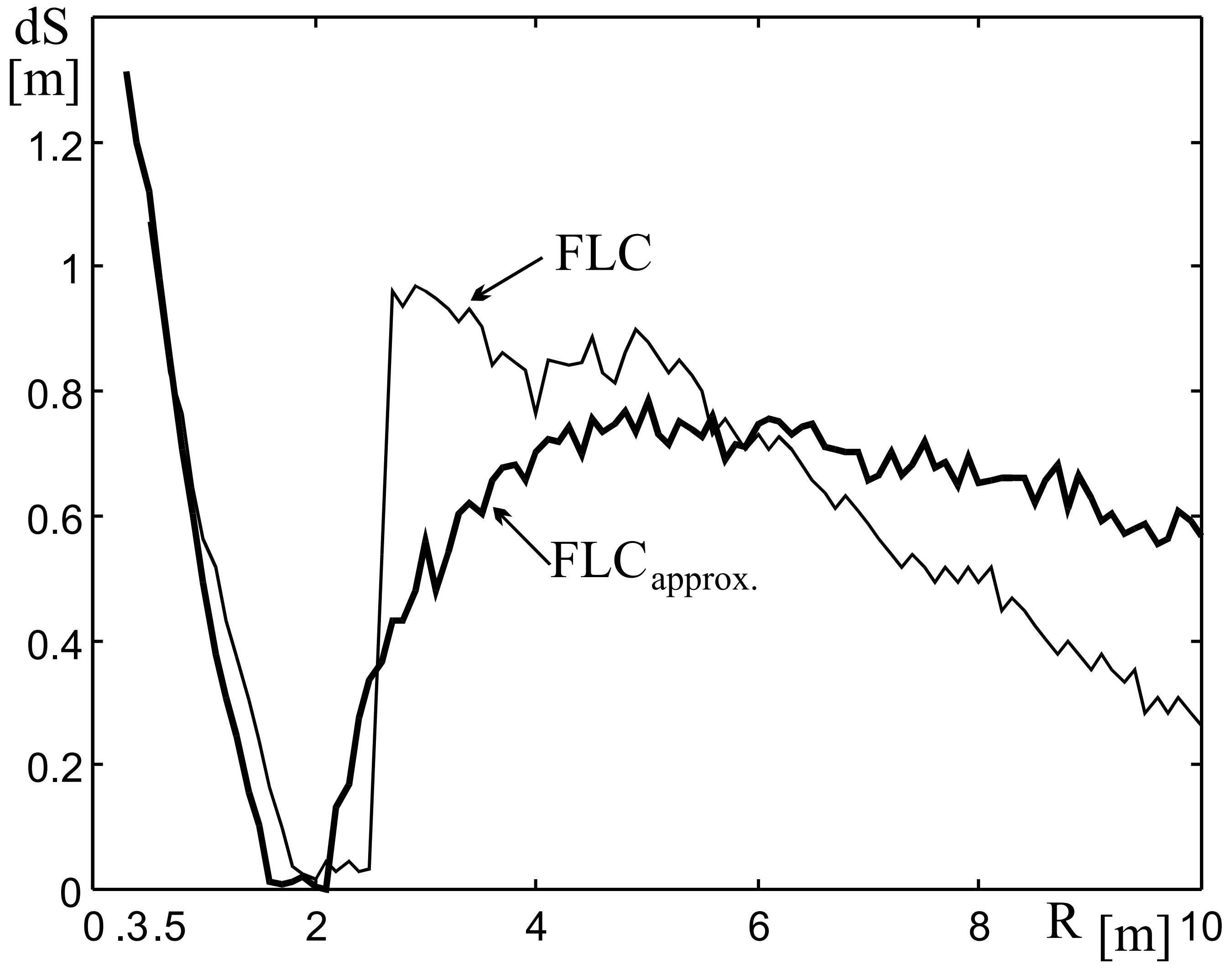
The **approximated minimal docking distance** of the simulated AGV on a **trial guide path** using the **approximate fuzzy reasoning based FLC path tracking strategy**:



Comparing the Simulated Results

On the trial guide path we have used, **there were no significant differences in minimal docking distances** of the two simulated implementations of the FLC (classical CRI and the proposed approximate fuzzy reasoning) path tracking strategies.

In both cases these results are always better than the minimal docking distance calculated for the optimal, single guide point based steering system.



Simulated results of the **minimal docking distances** (dS) using the **CRI based FLC** (FLC) and the **approximate fuzzy reasoning based** ($FLC_{approx.}$) **path tracking strategy in function of the trial guide path radius** (R)

Conclusions

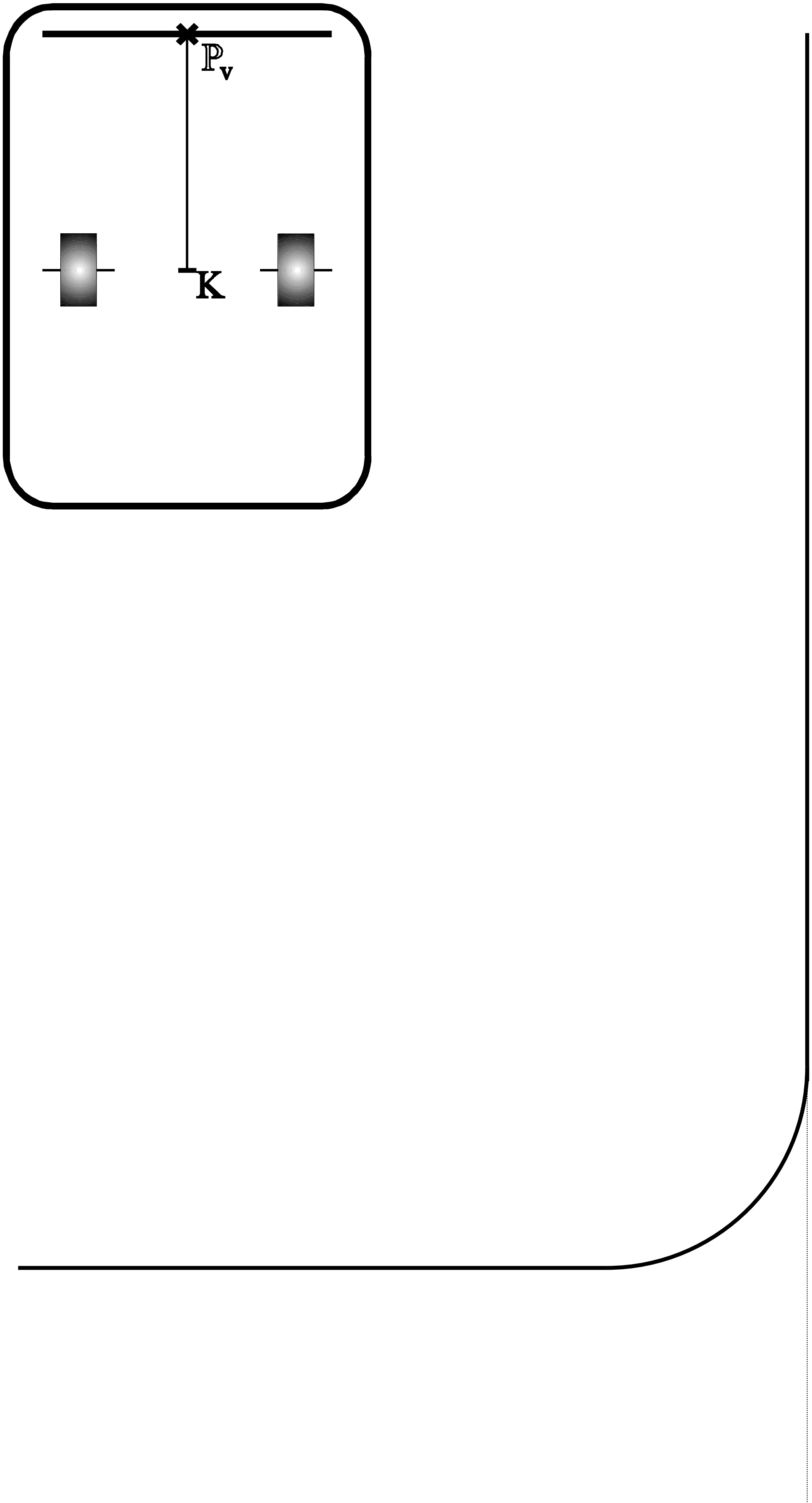
On the trial guide path we have used, **there were no significant differences in minimal docking distances** of the two simulated implementations of the FLC (classical CRI and the proposed approximate fuzzy reasoning) path tracking strategies.

This is the conclusion we were expected. **Both rulebases were fetched from the same "expert knowledge" describing the same path tracking strategy**, so the simulated results of the two solutions should not be differ dramatically from each other.

The main difference is the reduction in the number of the rules required for getting similar results. In spite of the radical reduction of the number of the fuzzy rules, there are no notable differences in the efficiency of the two solutions.

(In case of **steering from 49 to 12 rules**, in case of the **speed from 49 to 5 rules**.)

In other words it means, that **using the concept of vague environment in most cases we can build approximate fuzzy reasoning methods simple enough to be a good alternative of the classical Compositional Rule of Inference methods in practical applications**.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Application of the Approximate Fuzzy Reasoning Based on Interpolation in the Vague Environment of the Fuzzy Rulebase in the Fuzzy Logic Controlled Path Tracking Strategy of Differential Steered AGVs

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Approximate Fuzzy Reasoning Based on Interpolation in the Vague Environment of the Fuzzy Rulebase as a Practical Alternative of the Classical CRI

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