Knowledge-Based Control Systems
(SC4081)

Lecture 4: Knowledge based fuzzy control

Alfredo Núñez
Section of Railway Engineering
CiTG, Delft University of Technology
The Netherlands

a.a.nunezvicencio@tudelft.nl
tel: 015-27 89355

Robert Babuška
Delft Center for Systems and Control
3mE, Delft University of Technology
The Netherlands

r.babuska@tudelft.nl
tel: 015-27 85117

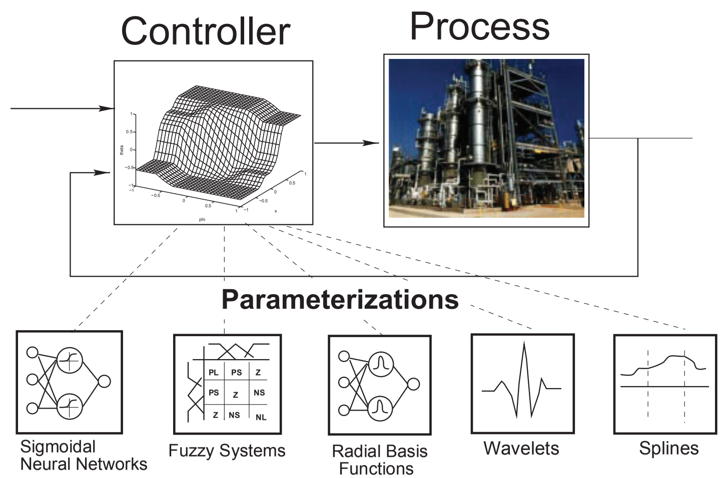
Outline

1. Direct fuzzy control.
2. Supervisory fuzzy control.
3. Software tools for fuzzy control.
4. Overview of applications.

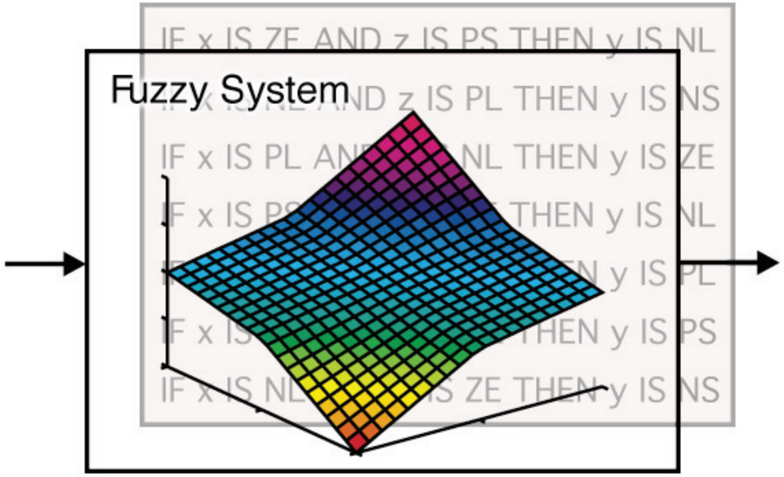
Fuzzy Control: Background

- controller designed by using If–Then rules instead of mathematical formulas (knowledge-based control),
- early motivation: mimic experienced operators,
- fuzzy reasoning: interpolation between discrete outputs,
- currently: also controllers designed on the basis of a fuzzy model (model-based fuzzy control),
- a fuzzy controller represents a *nonlinear* mapping (but completely deterministic!).

Parameterization of Nonlinear Controllers



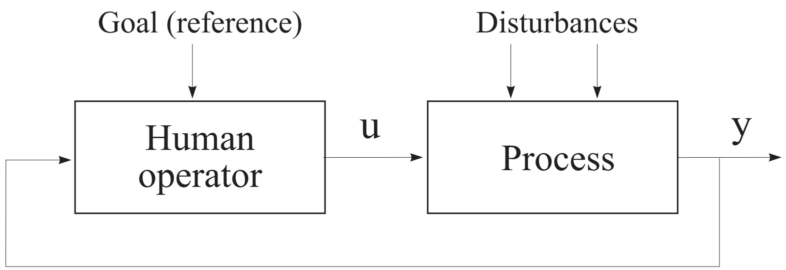
Fuzzy System is a Nonlinear Mapping



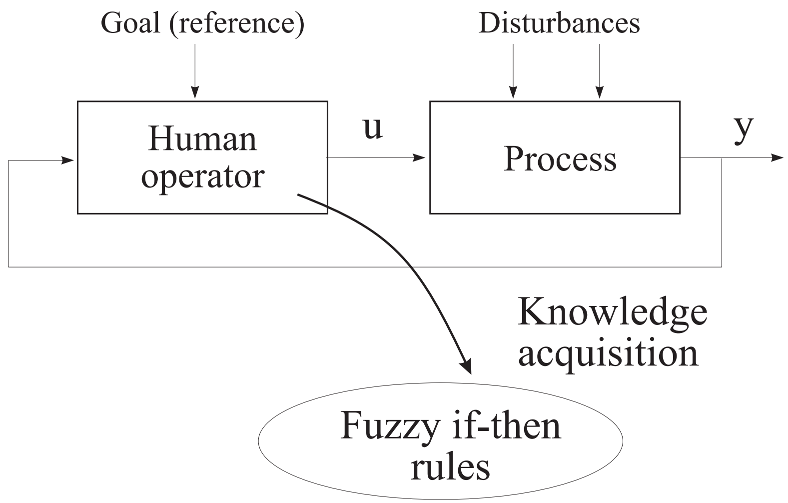
Basic Fuzzy Control Schemes

- Direct (low-level, Mamdani) fuzzy control
- Fuzzy supervisory (high-level, Takagi–Sugeno) control
- Fuzzy model-based control

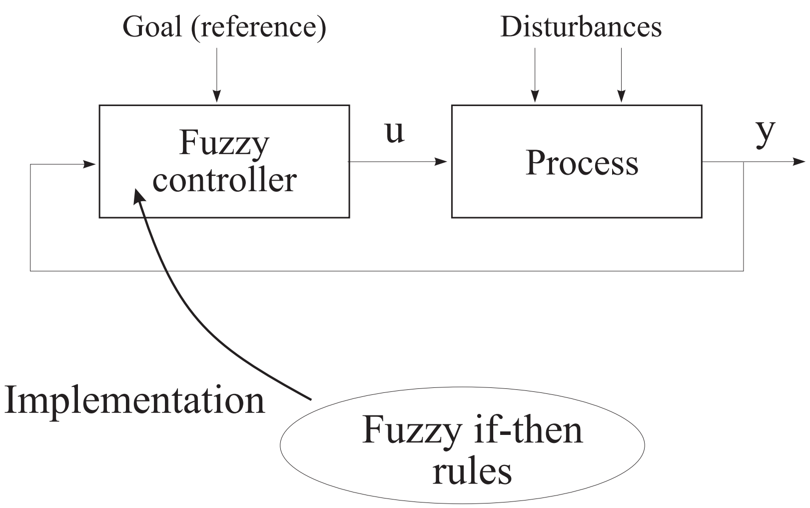
Process Controlled by Operators



Knowledge Acquisition



Direct Fuzzy Control

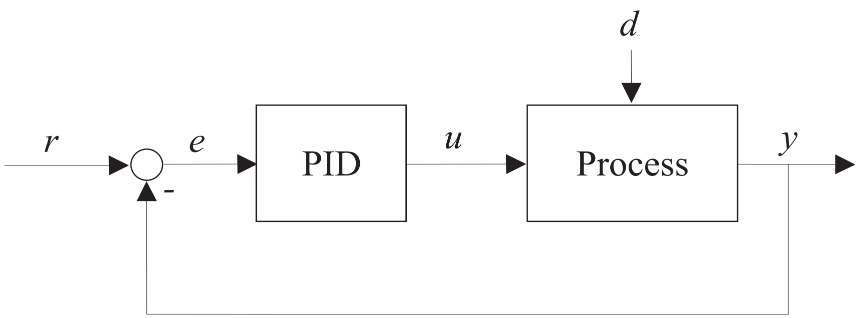


Example of Operator Knowledge

Case	Condition	Action to be taken	Reason
11	BZ OK	a. Decrease fuel rate slightly	To raise percentage of oxygen
	OX low		
	BE OK		
12	BZ OK	a. Reduce fuel rate	To increase percentage of oxygen for action b
	OX low	b. Reduce fan speed	To lower back-end temperature and
	BE high		maintain burning zone temperature
13	BZ OK	a. Increase fan speed	To raise back-end temperature
	OX OK	b. Increase fuel rate	To maintain burning zone temperature
	BE low		

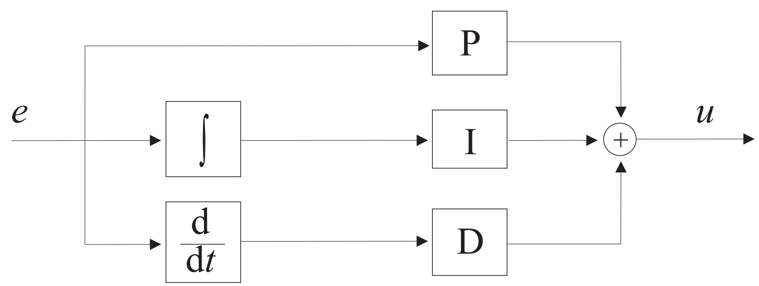
Extract from Peray's textbook for kiln operators (Oestergaard, 1999)

FLC Analogue to PID Control



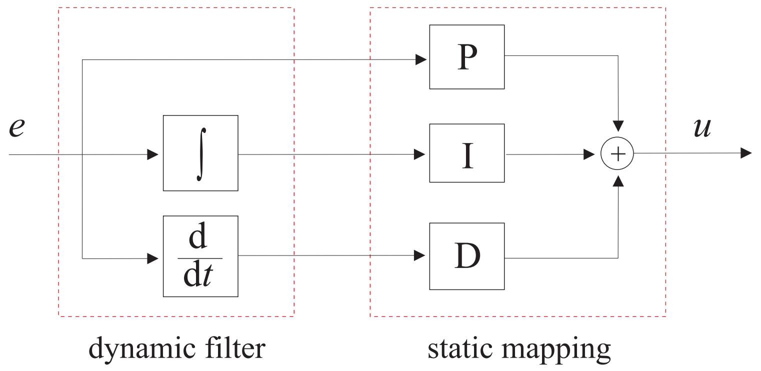
PID Control: Internal View

$$u(t) = Pe(t) + I\int_0^t e(\tau)d\tau + D\frac{de(t)}{dt}$$



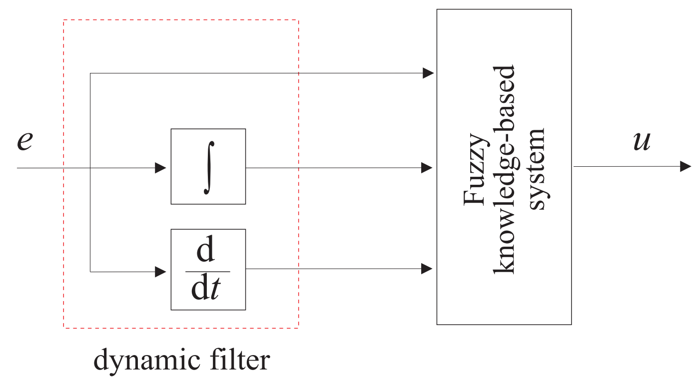
PID Control: Internal View

$$u(t) = Pe(t) + I \int_0^t e(\tau)d\tau + D\frac{de(t)}{dt}$$

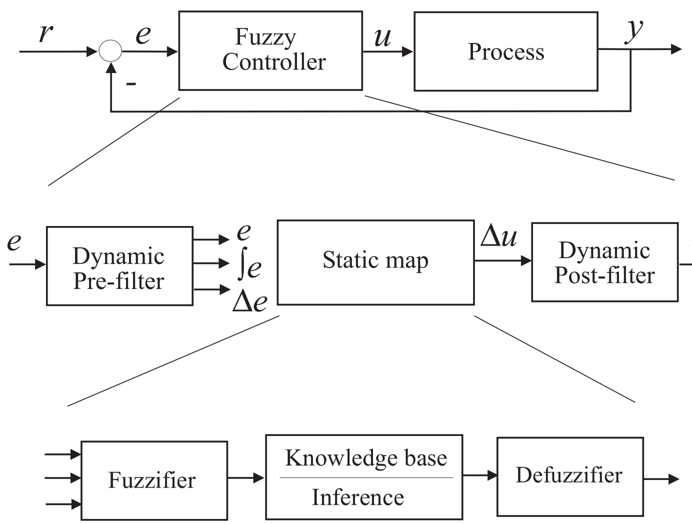


Fuzzy PID Control

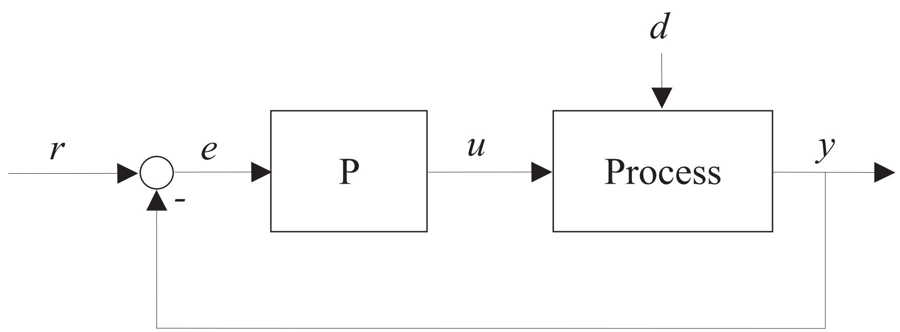
$$u(t) = f\left(e(t), \int_0^t e(\tau)d\tau, \frac{de(t)}{dt}\right)$$



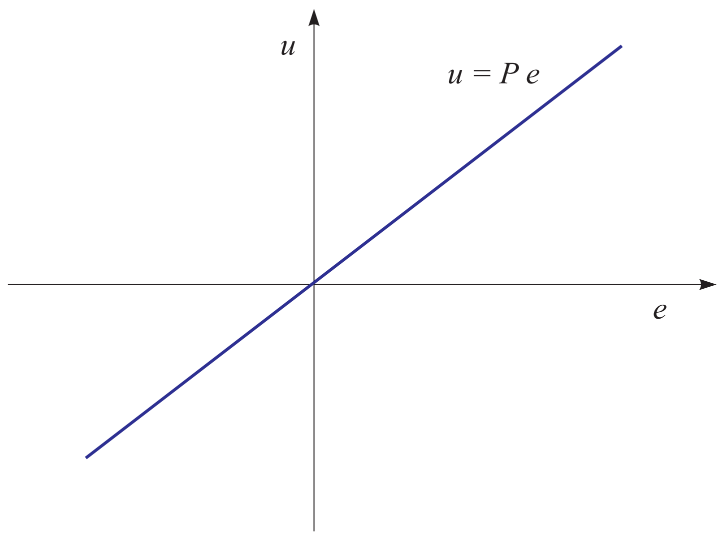
Fuzzy PID Control



Example: Proportional Control



Controller's Input–Output Mapping



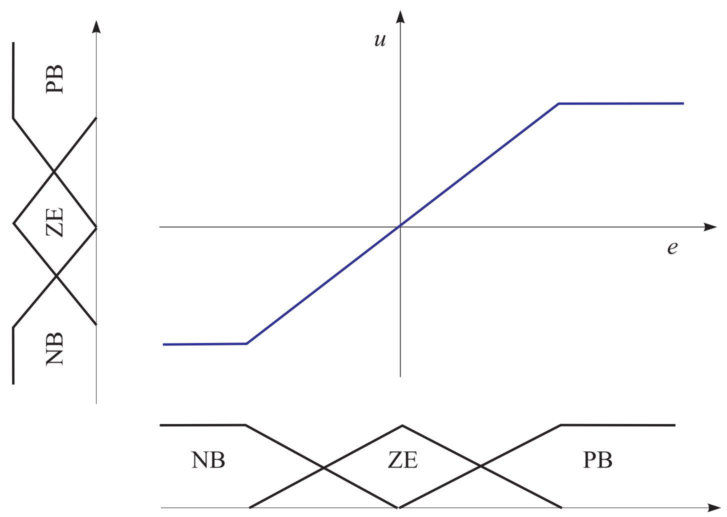
Fuzzy Proportional Control: Rules

If error is Negative Big then control input is Negative Big

If error is Positive Big then control input is Positive Big

If error is Zero then control input is Zero

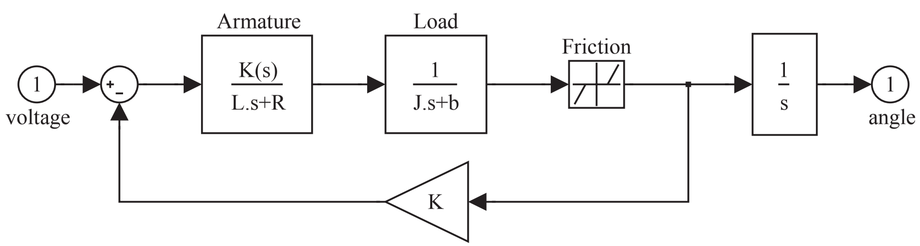
Controller's Input–Output Mapping



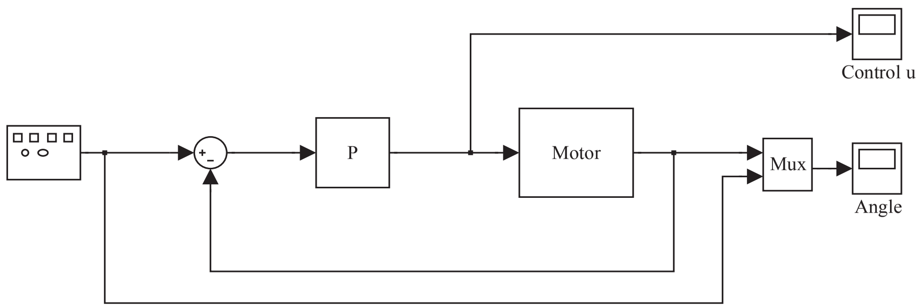
Example: Friction Compensation

1. DC motor with static friction.
2. Fuzzy rules to represent "normal" proportional control.
3. Additional rules to prevent undesirable states.

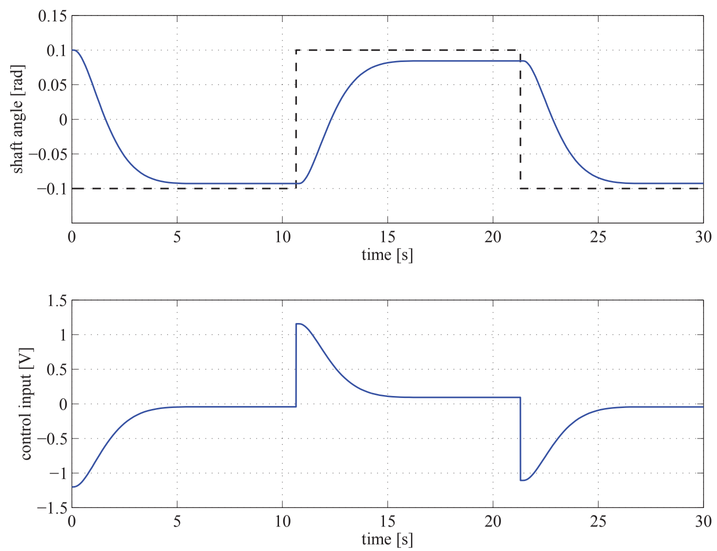
DC Motor: Model



Proportional Controller



Linear Control



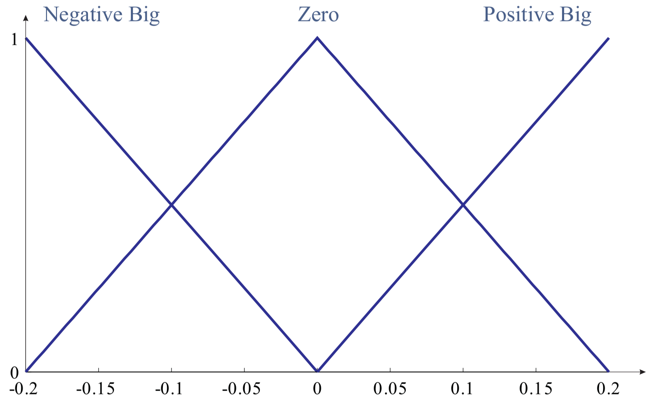
Fuzzy Control Rule Base

If error is Positive Big then control input is Positive Big;

If error is Negative Big then control input is Negative Big;

If error is Zero then control input is Zero;

Membership Functions for Error



Additional Rules

If error is Positive Big then control input is Positive Big;

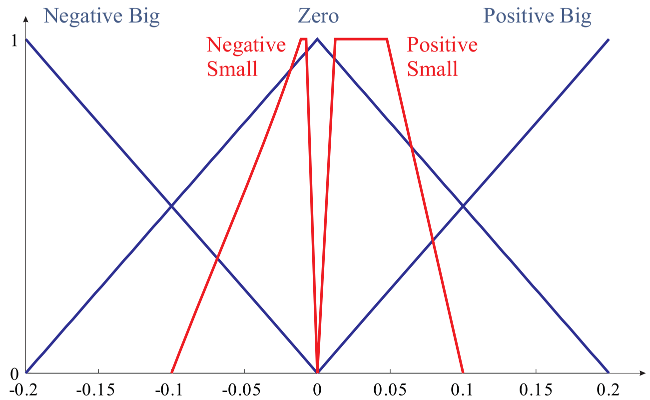
If error is Negative Big then control input is Negative Big;

If error is Zero then control input is Zero;

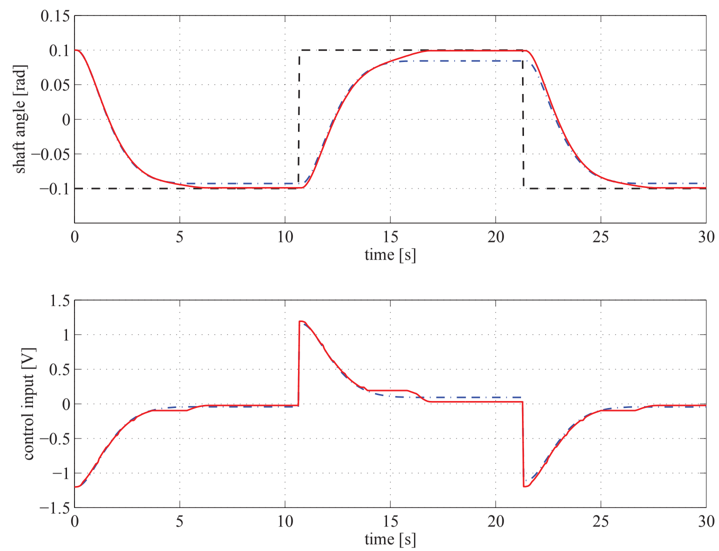
If error is Negative Small
then control input is not Negative Small;

If error is Positive Small
then control input is not Positive Small;

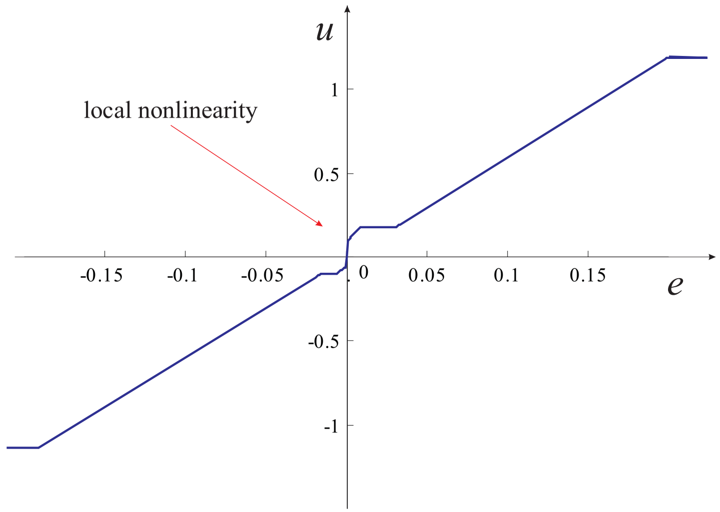
Membership Functions for Error



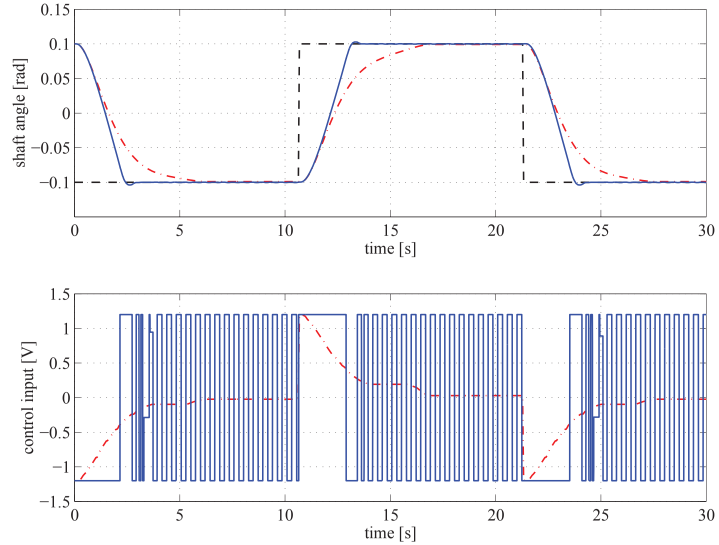
Fuzzy Control



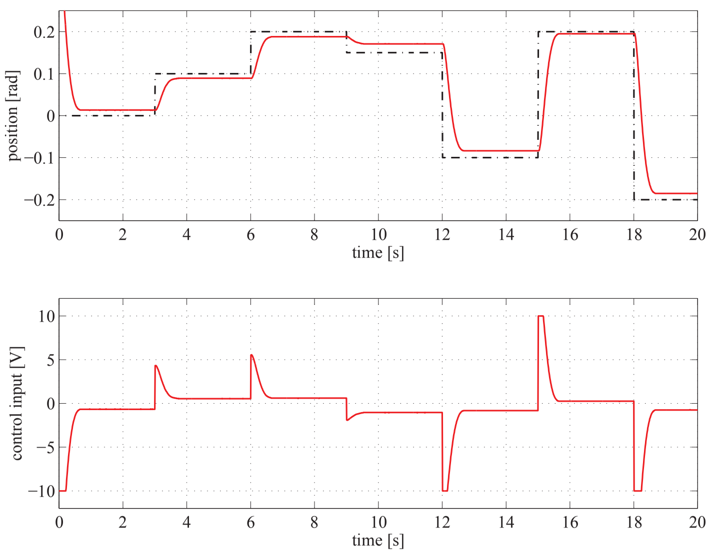
Input–Output Mapping of the Controller



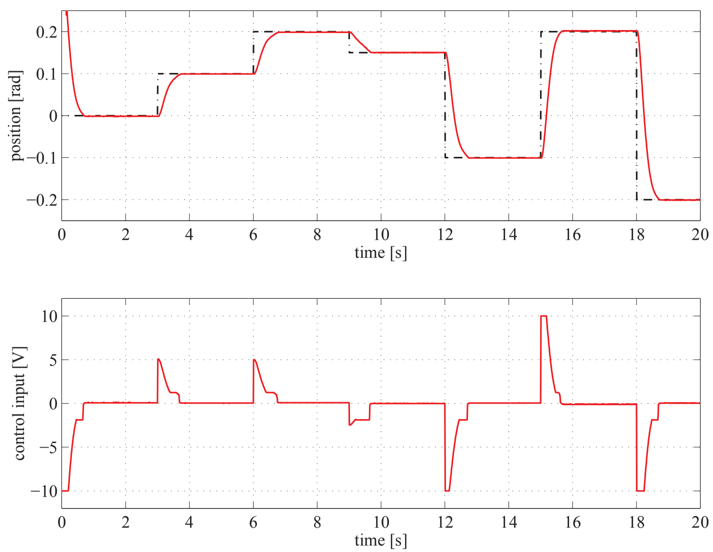
Another Solution: Sliding Mode Control



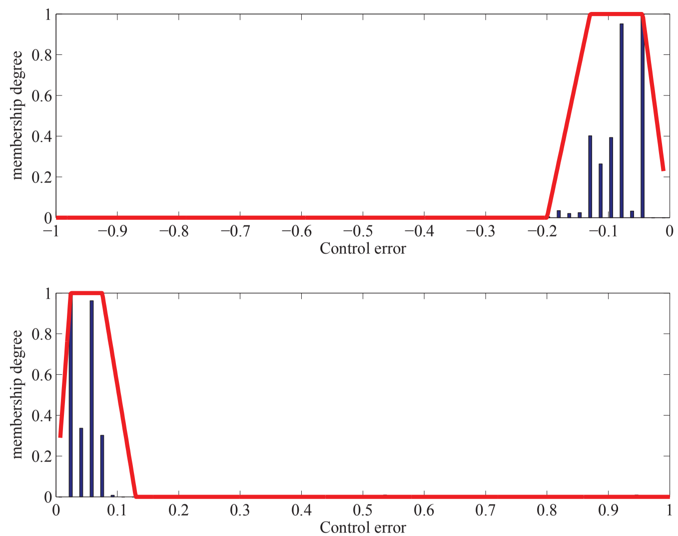
Experimental Results - Proportional Control



Experimental Results - Fuzzy Control



Membership Functions



Fuzzy PD Controller: Rule Table

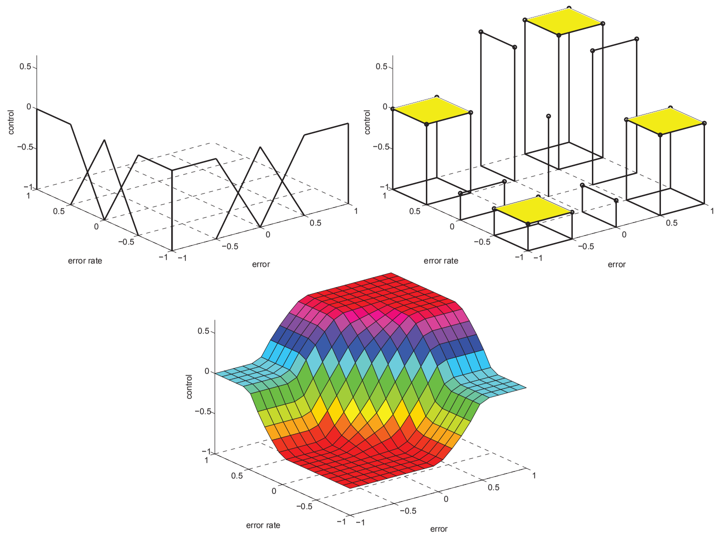
error rate

error

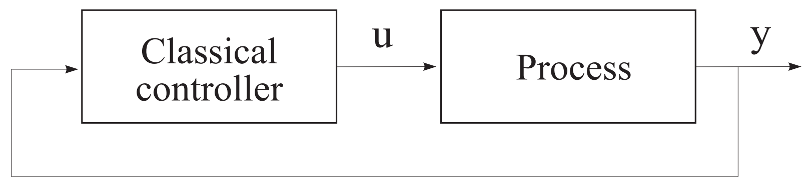
	NB	ZE	PB
NB	NB	NB	ZE
ZE	NB	ZE	PB
PB	ZE	PB	PB

R_{12}: **If** *error* **is NB and** *error rate* **is ZE then** *control* **is NB**

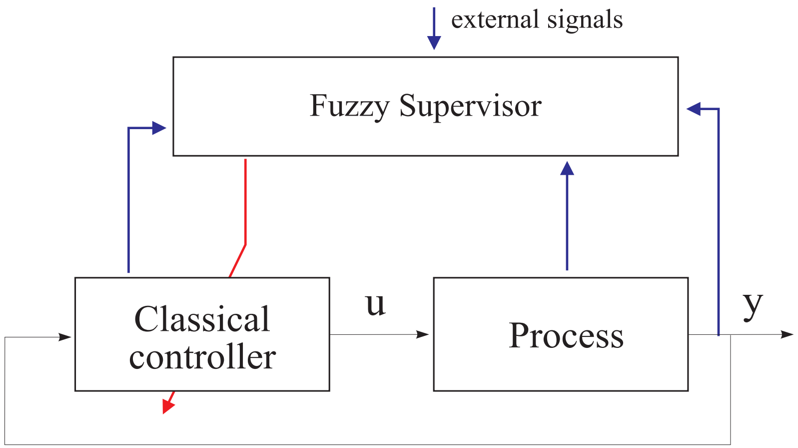
Fuzzy PD Controller – cont'd



Supervisory Fuzzy Control



Supervisory Fuzzy Control



Supervisory Control Rules: Example

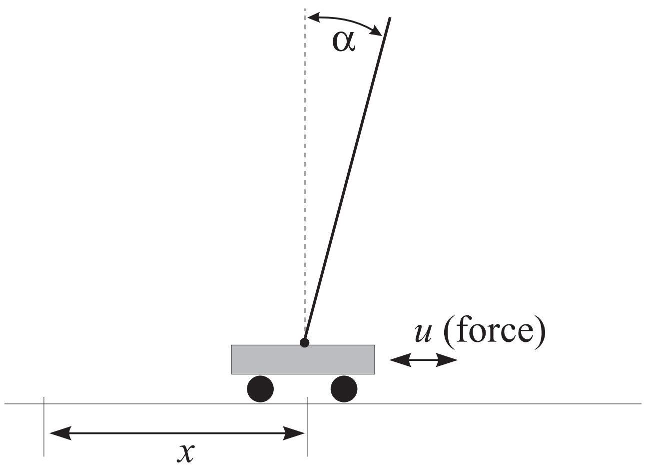
If process output is ***High***

then reduce proportional gain ***Slightly*** and

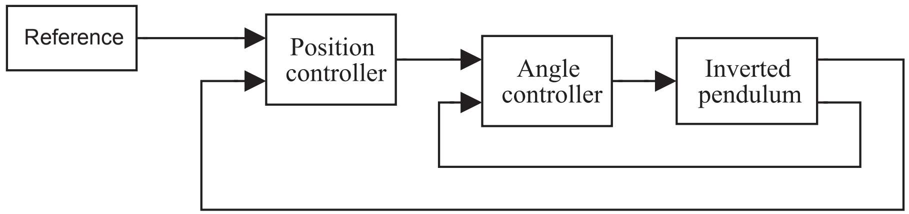
increase derivative gain ***Moderately***.

(Supervised PD controller)

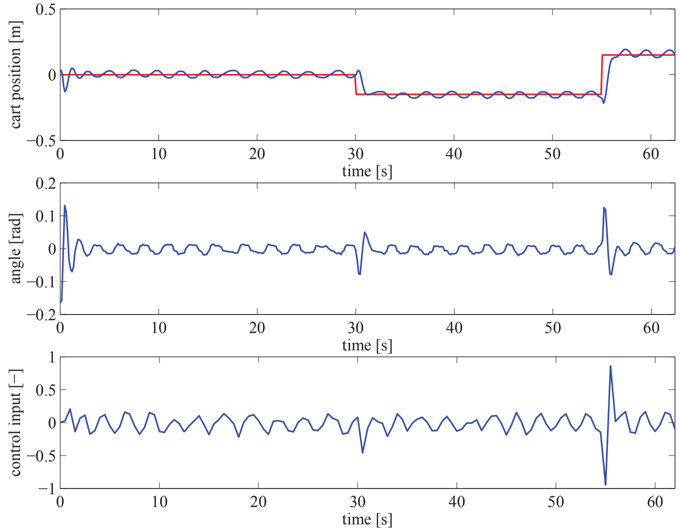
Example: Inverted Pendulum



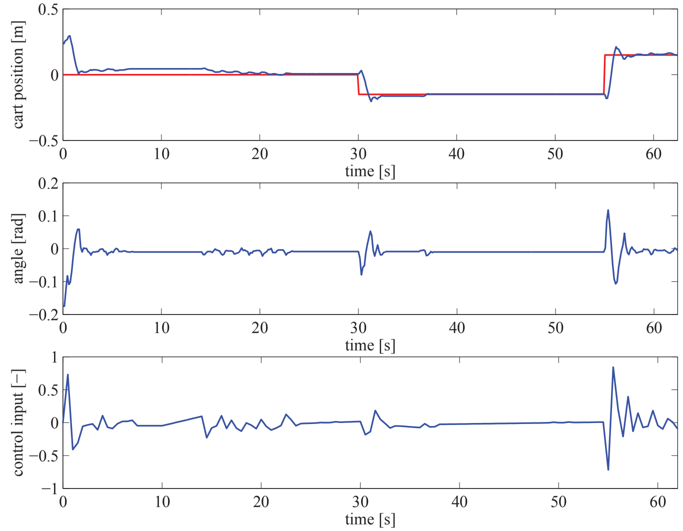
Cascade Control Scheme



Conventional PD controller



Fuzzy Supervised PD controller



Takagi–Sugeno Control

Takagi–Sugeno PD controller:

$$R_1: \ \textbf{If } r \textbf{ is Low then } u_L = P_L e + D_L \dot{e}$$
$$R_2: \ \textbf{If } r \textbf{ is High then } u_H = P_H e + D_H \dot{e}$$

$$u = \frac{\mu_L(r)\, u_L + \mu_H(r)\, u_H}{\mu_L(r) + \mu_H(r)} = \gamma_L(r)\, u_L + \gamma_H(r)\, u_H$$

Takagi–Sugeno Control

Takagi–Sugeno PD controller:

$$R_1: \ \textbf{If } r \textbf{ is Low then } u_L = P_L e + D_L \dot{e}$$
$$R_2: \ \textbf{If } r \textbf{ is High then } u_H = P_H e + D_H \dot{e}$$

$$u = \frac{\mu_L(r)\, u_L + \mu_H(r)\, u_H}{\mu_L(r) + \mu_H(r)} = \gamma_L(r)\, u_L + \gamma_H(r)\, u_H$$

$$= \{\gamma_L(r) P_L + \gamma_H(r) P_H\}\, e + \{\gamma_L(r) D_L + \gamma_H(r) D_H\}\, \dot{e}$$

Takagi–Sugeno Control

Takagi–Sugeno PD controller:

$$R_1: \ \textbf{If } r \textbf{ is Low then } u_L = P_L e + D_L \dot{e}$$
$$R_2: \ \textbf{If } r \textbf{ is High then } u_H = P_H e + D_H \dot{e}$$

$$u = \frac{\mu_L(r)\, u_L + \mu_H(r)\, u_H}{\mu_L(r) + \mu_H(r)} = \gamma_L(r)\, u_L + \gamma_H(r)\, u_H$$

$$= \{\gamma_L(r) P_L + \gamma_H(r) P_H\}\, e + \{\gamma_L(r) D_L + \gamma_H(r) D_H\}\, \dot{e}$$

$$= P(r) e + D(r) \dot{e},$$

Takagi–Sugeno Control

Takagi–Sugeno PD controller:

$$R_1: \ \textbf{If } r \textbf{ is Low then } u_L = P_L e + D_L \dot{e}$$
$$R_2: \ \textbf{If } r \textbf{ is High then } u_H = P_H e + D_H \dot{e}$$

$$u = \frac{\mu_L(r)\, u_L + \mu_H(r)\, u_H}{\mu_L(r) + \mu_H(r)} = \gamma_L(r)\, u_L + \gamma_H(r)\, u_H$$

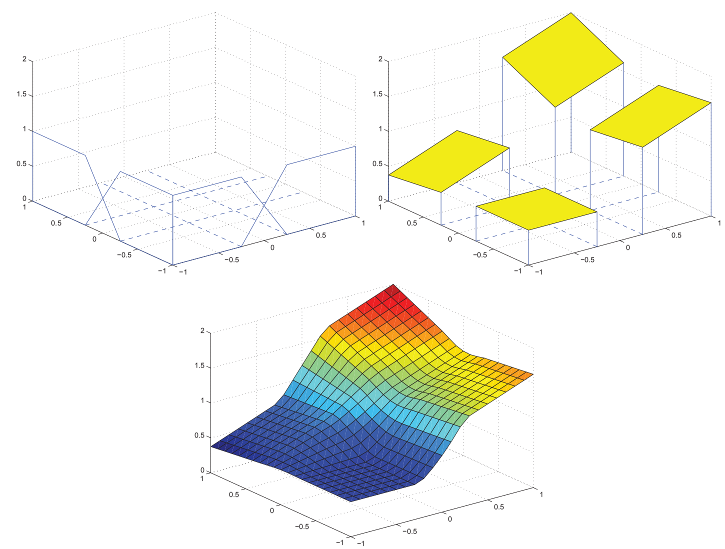
$$= \{\gamma_L(r) P_L + \gamma_H(r) P_H\}\, e + \{\gamma_L(r) D_L + \gamma_H(r) D_H\}\, \dot{e}$$

$$= P(r) e + D(r) \dot{e}, \qquad P(r) \in \mathrm{conv}(P_L, P_H), \ \ldots$$

Takagi–Sugeno Control is Gain Scheduling

Inputs → [*fuzzy scheduling*: Controller 1, Controller 2, …, Controller K] → Outputs

TS Control: Input–Output Mapping



TS Control: Example

1. Strongly nonlinear process (output-dependent gain).

2. Fuzzy supervisor to adjust the gain of a proportional controller.

3. Comparison with linear (fixed-gain) proportional control.

TS Control: Example

Nonlinear process:

$$\frac{d^3y(t)}{dt^3} + \frac{d^2y(t)}{dt^2} + \frac{dy(t)}{dt} = y^2(t)u(t)$$

Problems with linear control:

- stability and performance depend on process output
- re-tuning the controller does not help
- nonlinear control is the only solution

TS Control: Example

Goal: Design a controller to stabilize the process for a wide range of operating points ($y > 0$):

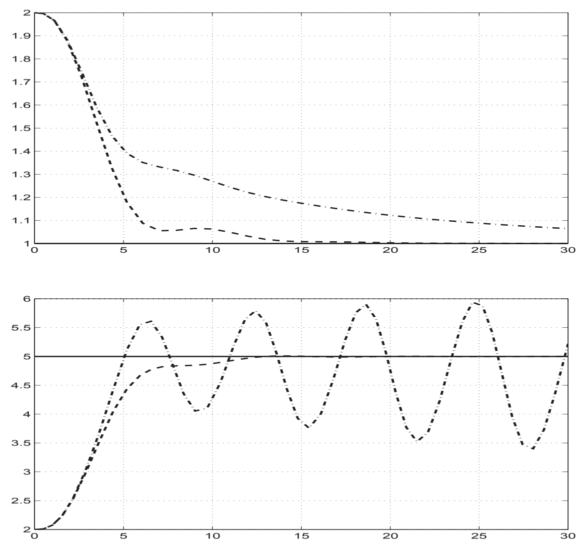
TS (proportional) control rules:

If y is Small then $u(k) = P_{Small} \cdot e(k)$

If y is Medium then $u(k) = P_{Medium} \cdot e(k)$

If y is Large then $u(k) = P_{Large} \cdot e(k)$

Comparison of Performance



Typical Applications

- Tune parameters of low-level controllers (auto-tuning).
- Improve performance of classical control (response-assisted PID).
- Adaptation, gain scheduling (aircraft control).

Typical Applications

- Tune parameters of low-level controllers (auto-tuning).
- Improve performance of classical control (response-assisted PID).
- Adaptation, gain scheduling (aircraft control).

\+ Enhancement of classical controllers.

\+ Interface between low-level and high-level control.

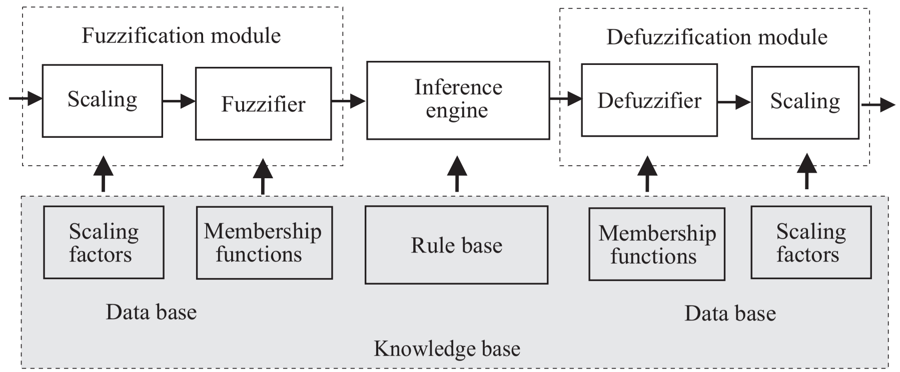
– Ad hoc approach, difficult analysis.

Fuzzy Control: Design Steps

control engineering approaches + heuristic knowledge

1. Determine inputs and outputs.
2. Define membership functions.
3. Design rule base.
4. Test (completeness, stability, performance).
5. Fine-tune the controller.

Parameters in a Fuzzy Controller



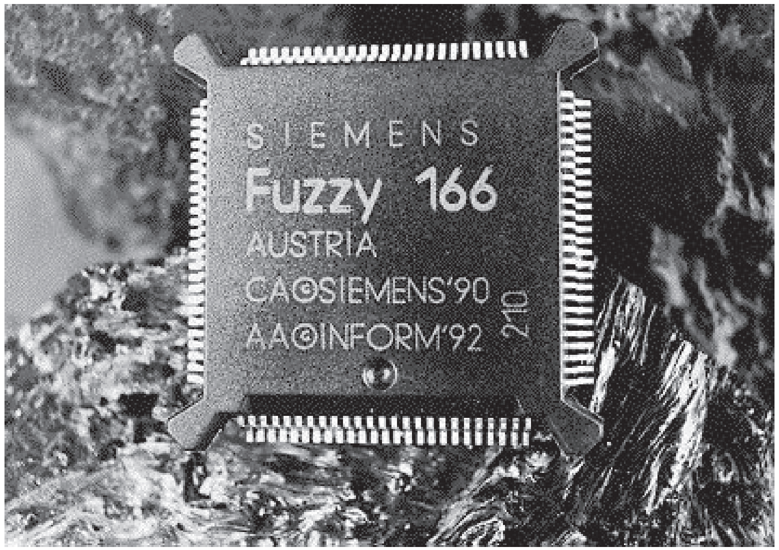
Software for Fuzzy Control

- Siefuzzy (Siemens)
- FuzzyTech (Inform)
- AB-Flex (Allen–Bradley)
- TDC-3000 (Honeywell)
- many others . . .

Hardware for Fuzzy Control

- Fuzzy logic-assisted PID controllers (Omron, Yokogawa, West Instruments).
- PLC coprocessors (Omron, Allen–Bradley).
- Dedicated hardware (fuzzy logic chips).

Dedicated Hardware

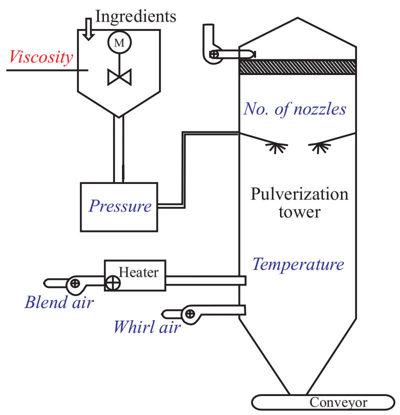


Applications of Fuzzy Control

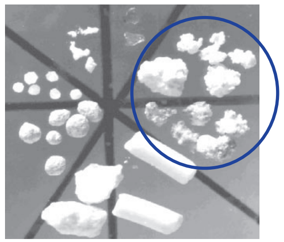
- process control (cement, chemical, glass)

Operator Support in Process Control

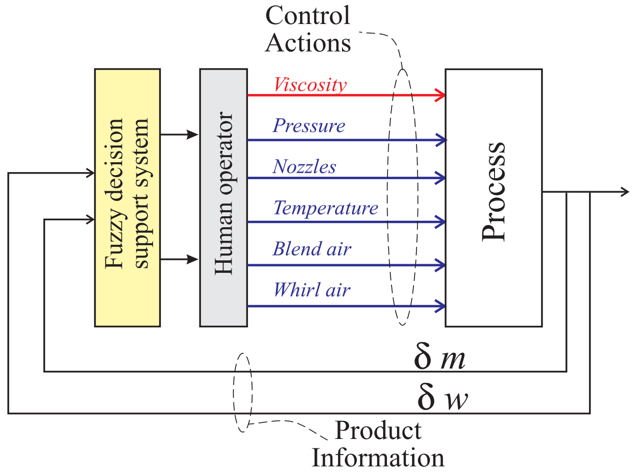
Production of detergents

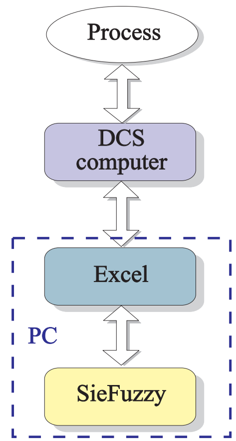


Quality:
- liter weight
- moist content

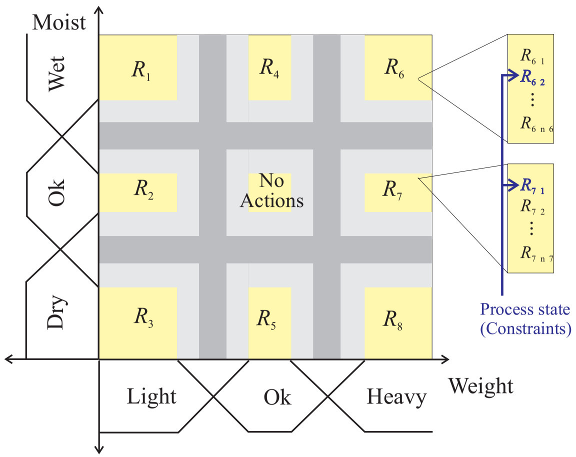


Fuzzy Decision Support System



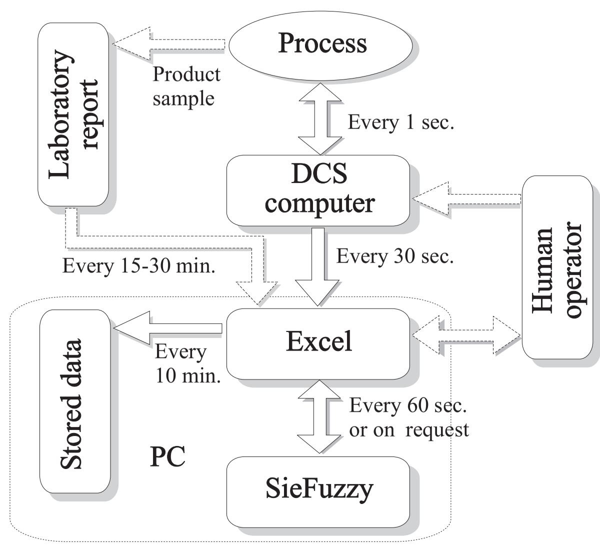


Fuzzy Rule Base

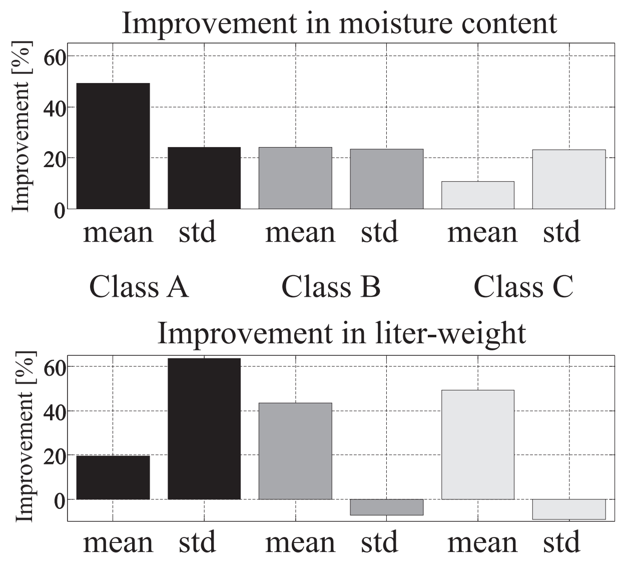


- Partitioning into error regions
- Each region has an ordered set of control rules

Implementation – Distributed Control System



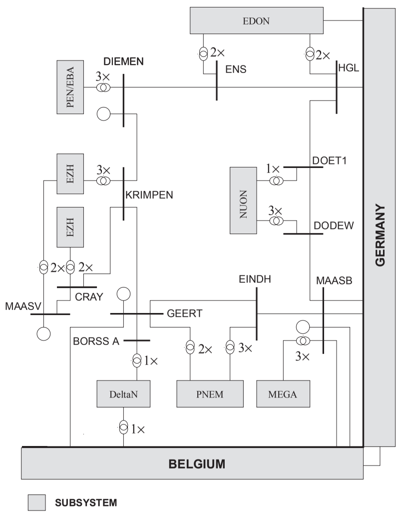
Evaluation: Results

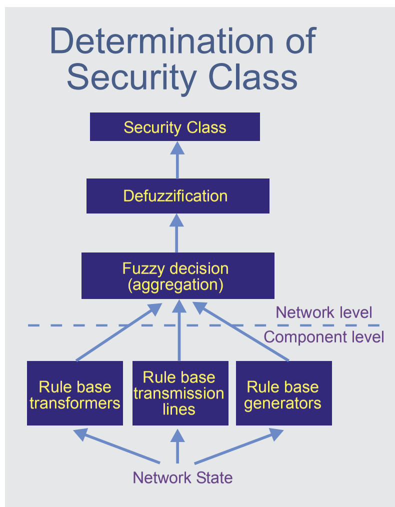


Applications of Fuzzy Control

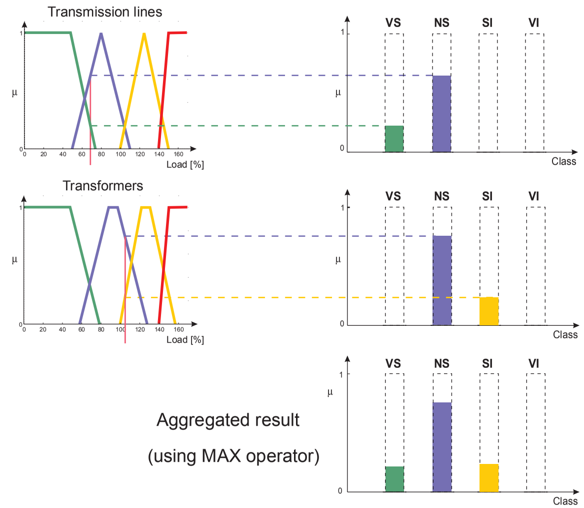
- process control (cement, chemical, glass)
- supervision (security of power distribution networks)

Security Assessment of a Power Network





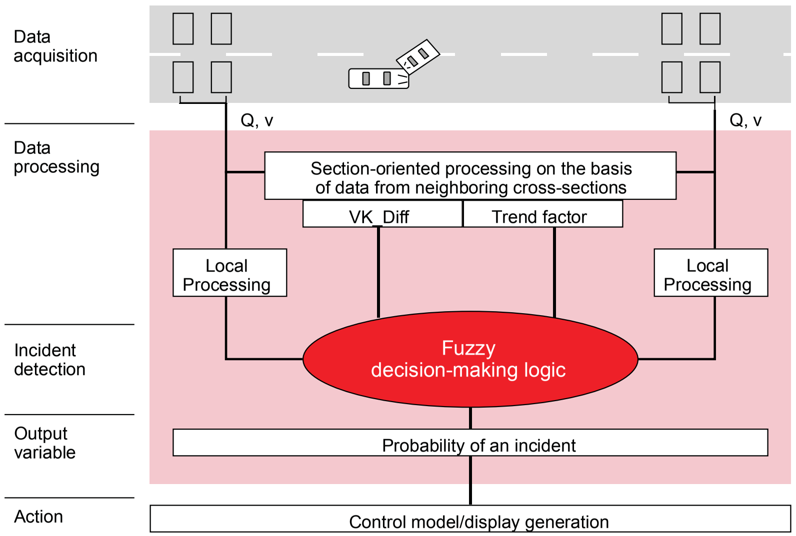
Fuzzy Decision



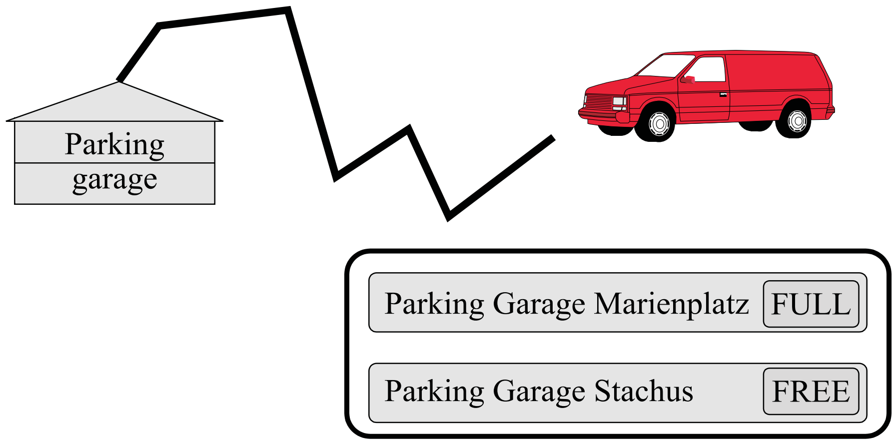
Applications of Fuzzy Control

- process control (cement, chemical, glass)
- supervision (security of power distribution networks)
- traffic management and control

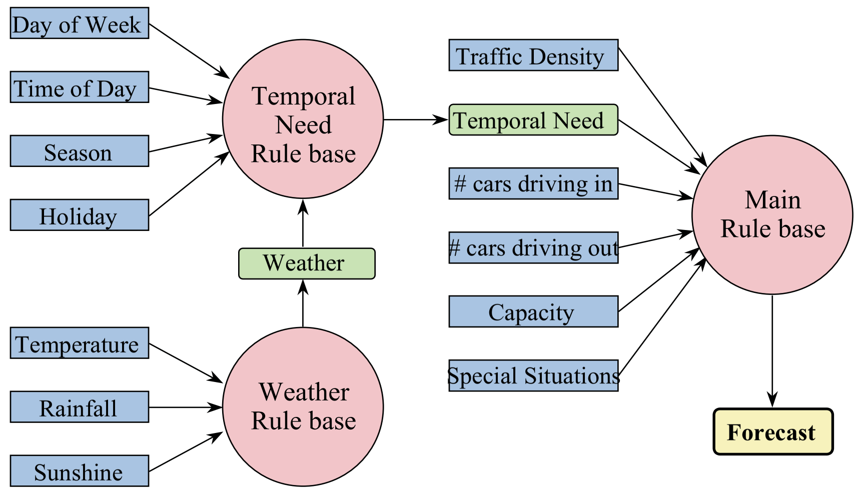
Traffic Management



Forecasting (Siemens)



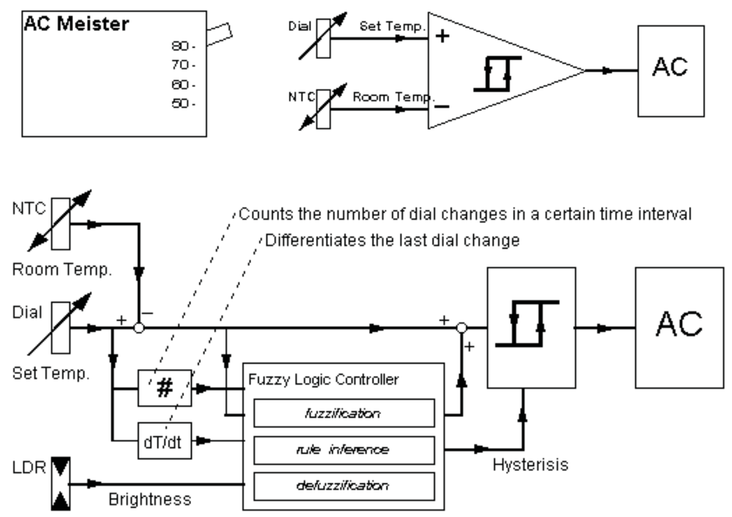
Knowledge-Based System



Applications of Fuzzy Control

- process control (cement, chemical, glass)
- supervision (security of power distribution networks)
- traffic management and control (prediction)
- consumer goods (camcoders, house appliances)

Intelligent Thermostat



Applications of Fuzzy Control

- process control (cement, chemical, glass)
- supervision (security of power distribution networks)
- traffic management and control (prediction)
- consumer goods (camcoders, house appliances)
- cars (engine management, automatic transmission)