# A Two-Variable Fuzzy Control Design with Application to an Air-Conditioning System

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A Two-Variable Fuzzy Control Design with Application to an Air-Conditioning System

S. Yordanova¹, D. Merazchiev¹ and L. Jain²

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Abstract: The air-conditioning systems are important for providing optimal conditions for work, human health and quality of living. At the same time they are one of the greatest household energy consumers. Therefore the Building Energy Management System sets high demands to their control, aiming at the reduction of the energy consumption while ensuring the indoor comfort. The classic control technique cannot satisfactory deal with the energy-efficient stabilization of the basic interacting microclimate parameters. The fuzzy logic approach offers intelligent means for stabilization of the coupled temperature, humidity and fresh air supply at low energy required. The aim of the present research is to develop a model-free design method for a two-variable PI fuzzy controller for temperature and humidity control that ensures indoor comfort and reduces energy consumption by supervisory fuzzy tuning.

Keywords: air-conditioning system, energy efficiency, MATLAB™, real time implementation, supervisory tuning, two-variable fuzzy control

1. Introduction and State-of-the-Art

The systems for heating, ventilation, and air-conditioning (HVAC) are very important in ensuring indoor comport, human health and quality of living. They reduce the harmful emissions, provide fresh air and stabilize the parameters of the microclimate. The basic factors that characterize the microclimate in a premise are the air temperature, humidity and speed as well as the concentration of carbon dioxide [1]. The main disturbances come from outside air supply parameters – temperature, humidity, speed (wind) etc., the premise (room, building) isolation and the inside factors related to population, draft, work, etc. According to the established standards [2, 3] the effective and also comfortable room ventilation air speed is limited between 0.25-0.15 m/s, the air temperature is good when between 20-24 °C and the air relative humidity (Rh) - in the range 40-60%. Temperature and Rh are bounded in the so called h-X diagram [1, 3]. The microclimate influences the concentration and productivity of the people that work or study in a premise. So, a control system is needed to ensure stabilization of the premise basic microclimate parameters using a HVAC system.

A typical HVAC system is shown in Fig.1. In the mixing section A the air from outside is

A – a mixing section; B – a fresh air filter; C – a recuperator section; D – a humidifier; E – a cooling section; F – a heating section; G – an air feeding fan; H – valves for influent air flow rate; I – a recuperator; J – a suction fan

Fig.1 Structure of a HVAC system
mixed with a part of the air taken out of the room in order to condition it (heat or cool). This preliminary conditioning via mixing utilizes the energy of the worked off air and thus contributes to energy efficiency. Here are also the valves for fresh air, which close, and the recycling valve, which opens, when the ventilator stops. The fresh air filter B cleans from particles. In the recuperator section C the fresh air is processed, utilizing the energy of the leaving air. Then come the humidifier D for increase of the relative humidity in winter time, the cooling section E for reducing the temperature and/or the humidity of the influent air, the heating section F for increasing the temperature of the feed air after the humidifier or for drying, the air feeding fan G, the valves H for influent air flow rate, the recuperator I and the suction fan J.

According to [2] in the United States and other developed countries, about one-third of all energy use can be attributed to buildings. It has been established that the HVAC systems are the highest energy consumers in a building and also with the greatest prospect for energy savings. Therefore the Building Energy Management System (BEMS) sets high demands to their control, aiming at reduction of the energy consumption while ensuring the indoor comfort.

The classic control technique using the basis of on-off or linear PID, PI, and P based controllers cannot satisfactory deal with the problem of energy-efficient stabilization of the basic interacting microclimate parameters. The control system performance is not good enough due to the multivariable character of the plant, its non-linearity, inertia, model uncertainty and numerous diverse disturbances [4, 5].

Recently intelligent control approaches based on the application of fuzzy logic and neural networks are employed to improve performance and also to reduce the energy required in stabilization of interacting temperature, humidity and fresh air supply [6, 7]. They require no plant model which makes them suitable for non-linear and multivariable plants [8, 9] and also insures robust control in presence of disturbances [10].

There are various fuzzy or neural-fuzzy control systems which differ in structure (number of linguistic variables and fuzzy units, rule bases, etc.), design methods, tuning facilities and fulfillment of the requirements for real time operation and simplicity of design and implementation. Many of them are bounded to temperature control only [3]. Often [3, 11, 12] the air temperature is substituted by thermal comfort estimated according to ISO 7730 by computed Predicted mean vote (PMV), which is a preferred generalized index that combines environmental variables – temperature, Rh, mean radiant temperature, air velocity, and individual parameters – metabolic rate and cloth index. Another estimate for thermal comfort is the least enthalpy estimator (LEE) is proposed In [13] a MISO FLC is suggested to control four variables (Rh, carbon dioxide, carbon monoxide and odours) by fan velocity. The implementation of MISO Mamdani and Sugeno FLCs is compared in [14].

Most of the reported FLCs are MIMO. Fuzzy MIMO approach is generally developed in [8, 15, 16]. It is applied to building HVAC systems in [16-19] and greenhouses [20, 21], where the output in the first is controlled by mixing of two flows of humid and dry air. Most are designed based on expert or intuitive approach [3, 11-15, 18-21]. Some suggest on–line tuning but more often off-line tuning procedures are developed involving:
- genetic or evolutionary algorithms for selection of rules and tuning of rule weight and membership functions [22-25];
- supervised training of artificial neural networks (ANN) of type Sugeno [17, 24, 26];
- prediction of ambient influences or plant output combined with a fuzzy model-based control [1, 27, 28];
- adaptation with reference model for scaling factors tuning in fuzzy PD controller for PMV, carbon dioxide concentration and illumination with reduced overshoot [12];
- supervisory fuzzy controllers for scaling factors tuning [29, 30] for MISO FLC.

The approaches consider energy efficiency requirements [1, 12, 16, 23- 25] basically in off-line tuning. They are included in the fitness function of evolutionary or genetic tuning algorithms for
lateral of membership functions, rule selection and minimization, scaling factors, etc., together with performance estimates of temperature stabilization in [24]; of PMV, carbon dioxide concentration and system stability in [12, 25].

The performance of the designed systems is assessed in simulation in [12, 13, 18, 22, 26], in real time experimentation on a plant model [15-17, 21] and a real world HVAC system and industrial controllers [19].

The analysis shows that the design is often specific, intuitive, complicated and off-line. Basic considerations are not treated together:
- all crucial microclimate variables to be controlled - air temperature, humidity and ventilation, in their coupling, making the plant multivariable in character;
- design criteria to be used, combining stability, performance and energy efficiency requirements.

The aim of the present investigation is to develop a systematic approach for the design of a stable MIMO PI-like fuzzy controller for the coupled air temperature and humidity in a laboratory HVAC system with a supervisory fuzzy auto-tuning of scaling gains from system performance and energy efficiency considerations with facility for on-line operation.

The paper is further structured in the following way. Section 2 deals with the theoretical background, related to fuzzy supervisory control, stability, robustness and energy efficiency. A design method of HVAC fuzzy two-variable controller with supervisory auto-tuning is developed and applied for the control of a laboratory HVAC system in Section 3. Section 4 shows results from real time experimentation and assessment of system performance and energy efficiency.

2. Theoretical Background and Problem Formulation

The general matrix block diagram of the proposed two-variable FLC consists of a basic PI FLC and a supervisory FLC as shown in Fig.2, where \( y(t), \ y_r, \ e(t), \ \dot{e}(t), \ o(t) \) and \( u(t) \) are the vector signals of the plant outputs, their references, the errors \( e_i = y_i - y_r \), \( i=1,2 \), their derivatives, the fuzzy units (FUs) outputs and the main channel FLCs control actions respectively. The basic FLC has a symmetrical structure with two identical main channel FLCs, which are cross-connected via the inputs or the outputs of their fuzzy units (FUs).

![Image of a general matrix block diagram of two-variable fuzzy PI/PID controller](image-url)

*Fig. 2 A general matrix block diagram of two-variable fuzzy PI/PID controller*
Table 1 Two-variable FLC channel connection

<table>
<thead>
<tr>
<th>Variant</th>
<th>C_v</th>
<th>C_{de}</th>
<th>C_{ds}</th>
<th>CC</th>
<th>FU_i input</th>
<th>FU_i output</th>
<th>Post processing</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>E</td>
<td></td>
<td></td>
<td>I</td>
<td>[e_i^n, e_j^n]</td>
<td>o_i^n</td>
<td>PI</td>
</tr>
<tr>
<td>2</td>
<td>I</td>
<td>E-I</td>
<td></td>
<td>I</td>
<td>[e_i^n, j_j^n]</td>
<td>o_i^n</td>
<td>PI</td>
</tr>
<tr>
<td>3</td>
<td></td>
<td></td>
<td>E</td>
<td>I</td>
<td>[d_i, d_j]</td>
<td>∆u_i^n</td>
<td>Integrator</td>
</tr>
<tr>
<td>4</td>
<td>I</td>
<td>I</td>
<td></td>
<td>E1</td>
<td>[e_i^n, e_j^n]</td>
<td>∆u_i^n</td>
<td>Integrator</td>
</tr>
</tbody>
</table>

Designations

\[ \text{Designations} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 1 \end{bmatrix}, \text{ - zero matrix}. \]
\[ \text{E} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & 1 & 1 \end{bmatrix}, \text{E1} = \begin{bmatrix} 1 & -1 \\ -1 & 1 \end{bmatrix}, \text{∆u_i - control rate,}
\]

Each main channel FLC includes:

1) a pre-processing unit for the FU inputs for computation of the derivative of error \( \dot{e}(t) \) or/and the signed distance \( d_s = e + \lambda \dot{e} \) when necessary, and for signals normalisation in the range \([-1, 1]\) by the help of the gains \( K_v, K_{de} \) and \( K_{ds} \);

2) a signal commutation unit to determine the specified FU inputs;

3) a FU with two inputs;

4) a cross control unit CC, and

5) a post-processing unit, generally expressed as a PID algorithm.

The cross connections between the main FLCs are described by the matrices \( C_v, C_{de}, C_{ds} \) and CC, which for the four basic variants of cross connections considered are given in Table 1 together with the determined by them inputs and output of each FU_i and the necessary post-processing in order to have main PI-like FLCs. In variants 1-3 the cross connection is accomplished via the inputs to the FUs which are the main channel error and the cross channel error or main channel error and the cross channel plant output derivative or main channel signed distance and cross channel signed distance respectively, while in variant 4 the cross connection is via the outputs of the FUs and the inputs are the main channel error and derivative of error.

The main channel FLC can be made also PID-like only by assigning another post-processing for given FU inputs on the base of the general PID algorithm.

Each of the two FLCs in the basic FLC can be designed according the procedure in [31] to ensure system stability and robustness. First the FU of the two-input FLC is designed using standard empirical rules for the membership functions and the fuzzy rule base.

Then the two-input FLC is equivalently represented by a single input (SI) FLC. This is based on the \( \alpha \)-\( \epsilon \) (or \( \Delta e \)) projection of the designed FU control surface which is enclosed within a sector with the exception for a disk around the origin. The equivalent SI FLC has the steepest control curve from all curves in the projection that passes through the origin. It is easily tuned applying a modification of the Popov stability criterion, expressed in the following. All dynamic parts from pre- and post-processing, which contain the FLC tuning parameters, and an estimated Ziegler-Nichols plant model, make an augmented LTI plant. This augmented plant is stabilized by a gain feedback. Then its Nyquist plot is obtained. Over it for each frequency are laid disks of uncertainties, determined by estimated plant model uncertainty. The FLC tuning parameters should satisfy the requirement the Nyquist plot with the disks around each frequency point to lie to the right and below the Popov line, determined by the slopes of the sector-bounding lines.

Finally returning to the initial two-input FLC with the same tuning parameters correcting only the post-processing gain by shrinking it to a degree, which makes the disk around the origin in the control surface projection, where the requirement of Popov criterion for sector-bounded nonlinearity the violated, acceptably small.
This stability approach in the FLC design is simple and convenient for complex plants - MIMO nonlinear, with time delay and model uncertainty as no reliable simple enough classical plant model is available or can be derived.

The supervision tuning principle has been developed for a MISO PI FLC in [30]. Usually the scaling factors are auto-tuned on the basis of the closed loop system performance, estimated by measurable variables such as rising time $t_r$, settling time $t_s$, overshoot $\sigma$, maximal dynamic deviation $|y_{nl}|=|y_{max}-y_{i}|$, integral square error $ISE = \int_{0}^{t_f} e^2(t)dt$, etc. In [30] the auto-tuning considers $K_c = f_1(\sigma)$, $K_{dc} = f_2(ISE)$ and $K_{ma} = f_3[\max |\Delta u^n|]$. Most performance measures used require a registration for a step response time before a retuning decision and therefore are convenient only for off-line tuning. Suitable for on-line tuning performance measures can be based on magnitude or maximum of the absolute values of measurable variables such as system error, output, derivatives, control action, etc.

The energy efficiency is related with fast transient response without overshoot and minimal required control action. In [16] the following global energy consumption measure is suggested:

$$ I^k = a \sum_{i=1}^{N} U^k_i + b \sum_{i=1}^{N} t^k_i + c \sum_{i=1}^{N} \frac{|y^k_m|}{\sum_{i=1}^{N} \sum_{k=1}^{N} |y^k_m|}, $$

(1)

where $U^k = \sum_{i=1}^{N} \int_{0}^{t^k_i} [u^k_i(t)] dt$ is the total control effort from the $k^{th}$ step response, $k=1\ldots N$, computed from the magnitude of the control action $|u^k_i|$ for the time of the step response $t^k$ for the two channels $i=1, 2$, $t^k = \sum_{i=1}^{N} t^k_{si}$, $|y^k_m| = \sum_{i=1}^{N} |y^k_m|$. The smaller $I^k$ is the more energy efficient the FLC system is during the $k^{th}$ step response.

The problem is to apply the above mentioned criteria and methods in developing a simple, transparent and easy to employ design procedure of FLC for the coupled variables relative humidity $y_1$ and temperature $y_2$, which ensures indoor comfort with lowest possible energy consumption.

### 3. Method for design of HVAC fuzzy two-variable controller with supervisory auto-tuning

Input parameters for the design are:
- expert estimates of the Ziegler-Nichols (Z-N) models on main channels of the plant;
- the worst expected variations of their parameters with respect to stability – increase of gains and time delays and decrease of time constants;
- maximal expected absolute system errors $|e_{max}|$.

The design method consists of the following steps.

1. Design of MIMO FLC system structure from variants 1-4 or other.

As a result the FU's inputs and outputs are determined as well as the post-processing operator. The FU units have normalized in the range [-1, 1] inputs and outputs.

2. Design of each of the main channels FLCs

2.1. Design of the FU
Fig. 3 h-X diagram of the relationship between relative humidity in % and temperature in °C

Fig. 4 Control surface (left) and its [o-main channel input] projection (right)

The membership functions (MFs) are selected with standard shape and parameters. The rule base is derived considering the cross connections in the plant by using the h-X diagram in Fig.3. The comfort area is enclosed between Rh of 40-60% and temperature of 20-24°C. By increasing the temperature (vertical arrow) the humidity decreases. The increase of Rh (the other arrow) is accompanied by a decrease in the temperature. This reveals the type of coupling between the two output variables of the plant – the both cross connections are negative in sign.

2.2. Determination of the equivalent SI FLC

The equivalent SI FLC is determined by \((K, r)\) - the slopes of the lines that enclose the \([\text{FU output}]-\text{(main channel input to the FU)}\) projection of the control surface in a sector. Besides, the diameter \(\delta\) of the disk around the origin, where the projection sector-bounded condition is violated, has to be recorded, as shown in Fig.4.

2.3. Computation of the SI FLC tuning parameters

The SI FLC tuning parameters \(q_{\text{SI FLC}}\) are computed from the modified Popov robust stability criterion. For example for variant 4 \(q_{\text{SI FLC}}=[K_\alpha, T_d, K_a]\), where \(K_d\) and \(T_d\) are the parameters of a first order noise-resistive differentiator for the error derivative \(W_d(s) = K_dT_d(s(T_dS + 1)^{-1}\) in the pre-processing and an integrator with gain \(K_\alpha\) in the post-processing, etc. This requires expert estimate of a Ziegler-Nichols plant model with ranges for its parameters that define the plant model uncertainty.
2.4. Return to the parameters of the initial two-input FLC \( q_{FLC} \) by reducing the higher of the two channels post-processing gain in order to compensate the \( \delta \)-violation of the sector-bounded projection condition, for example for variant 4 \( K_{a1} = k(\delta)K_a \), where \( k(\delta) = 0.1 + 0.3(\delta_{\text{max}}/\delta - 1) \).

2.5. Computation of the normalization gains using the maximal expected absolute error \( |e_{\text{max}}| \).

3. Design of supervisory FLC for the MIMO basic FLC in order to improve system performance and compensate variable plant parameters and ambient influences.

The supervisory FLC consists of several independent SISO FUs and allows on-line or off-line auto-tuning of the inputs scaling and the post-processing gains from criteria for optimal system performance and energy efficiency within the stability margins of the closed loop system with the basic FLC.

3.1. Design of supervisory FLC structure

This requires specification of:

- the inputs to the FUs - proper performance measures, which are computed on the basis of measured system variables and consider the step response performance and the energy consumption indicators, thus multi-criteria optimization can be performed. The inputs are defined in absolute universes of discourse, which should be clearly defined.

- the corresponding FUs outputs - scaling factors \( k_s \) for dynamic correction of the basic FLC gains \( K_s \) and their ranges (defined universes of discourse);

- the expression for correction of the auto-tuned gains - additive, multiplicative or hybrid, linear or nonlinear.

3.2. Design of the independent FUs

3.3. Selection of auto-tuning mode – on-line or off-line.

In off-line mode the designed two-variable FLC with the supervisory fuzzy auto-tuning is first connected to a built and validated Sugeno plant model, developed beforehand by training a Sugeno type ANN or optimizing MFs and parameters by Genetic Algorithms (GA) using collected input-output data from the operation of the plant. After some period of operation the mean values for the auto-tuned gains are computed and assigned to the basic FLC, the supervisory FLC is disconnected and the basic FLC is connected to the real plant. This step of building a Sugeno plant model, connecting the FLC to the model for initial auto-tuning and returning to the real plant with mean values for the FLC gains may be repeated on demand.

In on-line mode the designed two-variable FLC with the supervisory fuzzy auto-tuning is connected to the plant. The same simplification is possible here too - fixing computed for some period of operation mean values for the auto-tuned gains on the basic FLC and disconnecting the supervisory FLC.

This procedure is applied for the design of a two-variable FLC with supervising FLC of the relative humidity (first main channel) and the temperature of a developed laboratory HVAC system, shown in Fig.5. The plant consists of two sections – the first is electrical heating and the second - a supersonic humidifier and a chamber with temperature and humidity sensors and the corresponding transmitters. There are four fans - at the input section, between the sections, between the second section and the chamber and at the output. The heater, the humidifier and the fans are controlled via Solid State Relays (SSR) by: 1) a computer algorithm with pulse-width modulated control action, completed in a Simulink model of MATLAB\textsuperscript{TM}, and an interfacing Data Acquisition (DAQ) board between the computer and the SSR; 2) programmable logic controller (PLC).

Following the steps of the procedure the following results are obtained.
The input data for the design are:

- plant Z-N model nominal and worst varied parameters (increased $K$ and $\tau$ and decreased $T$), given in Table 2.

- maximal expected absolute system error $|e_{\text{max}}|=5\%\text{Rh}$ and $|e_{\text{max}}|=2\, ^\circ\text{C}$.

1. Variant 2 from Table 1 is selected for the basic two-variable FLC structure with inputs to the FUs the main channel error $e_i(t)$, the cross channel output derivative $\dot{y}_j(t)$ and PI post-processing. The output derivatives are obtained using first order differentiator with transfer function $W_d(s) = \frac{K_d T_d s}{s + 1}$. The differentiator parameters $T_d=10s$ and $K_d=1$ are selected from requirements for noise filtration and good differentiation of the smooth changing outputs, which should be felt at sample period $d_T$ at the FUs inputs. Therefore $T_d$ should be much smaller than the smallest plant time constant and greater than several times the sample period - $N.d_T<<100$, $N=3\div10$, $d_T<0.1\text{min}(\text{smallest } T_{ii}, \text{smallest } \tau_{ii})=0.5s$.

2. The design of the two main channels FLCs is identical

The MFs and the rule base of the FUs of Mamdani FLCs are shown in Fig. 6. The control surface and the projection for the first and the second main channel FLC are the same, given in Fig. 4.

The SI FLC tuning parameters $q_{\text{SI FLC}}=[K_p, K_i]$ are the parameters of the post-processing PI algorithm. They are computed from the modified Popov robust stability criterion and are given in Table 2. The initial two-input FLC parameters are the same with the exception of the corrected greater post-processing gain $K_{p2FLC}=k(\delta).K_{p2SI} (K_{p2SI}=1.9, k(\delta)=0.3)$ and are shown in Table 2 together with the normalization gains $K_{c1}, K_{d1}, K_{c2}$ and $K_{d2}$ for the given maximal expected errors magnitude.

<table>
<thead>
<tr>
<th>Table 2</th>
<th>Ziegler-Nichols models parameters, obtained from experimental step responses</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Main channel</strong></td>
<td><strong>Plant model parameters</strong></td>
</tr>
<tr>
<td></td>
<td><strong>Gain $K$</strong></td>
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<tr>
<td><strong>Nominal</strong></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>$K_{v11}=4.5%/V$</td>
</tr>
<tr>
<td>2</td>
<td>$K_{v22}=2^\circ\text{C}/V$</td>
</tr>
<tr>
<td><strong>Worst varied</strong></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>$K_{v11}=5%/V$</td>
</tr>
<tr>
<td>2</td>
<td>$K_{v22}=2.1^\circ\text{C}/V$</td>
</tr>
</tbody>
</table>
3. The designed supervisory FLC consists of three FUs with inputs and outputs, MFs and fuzzy rules, shown in Fig.7. The inputs $P_1=[\Delta u_i]$, $P_2=[u_i]$ are related to system performance and $P_3=[u_i^2]$ - to energy efficiency. The outputs are the scaling gains $k_{pi}$, $k_{dyj}$ and $k_{pi}$ for $K_{ei}$, $K_{dyj}$ and $K_{pi}$ respectively. The ranges [0.5, 1.5] of the outputs MFs ensure that the tuned values for $K_{ei}$, $K_{dyj}$ and $K_{pi}$ from robust stability correspond to the medium (norm) term $mk$. The auto-tuning is expressed in continuous time scaling of the gains – the corrected gains are $K_{ei}^c=k_{ei}, K_{dyj}^c=k_{dyj}, K_{pi}^c=k_{pi}, K_{pi}$. 

The mode of auto-tuning is off-line. It is carried out on a TSK plant model, derived by means of GA using collected plant input-output data from its manual operation. The two-variable FLC with the supervisory FLC is designed by the help of Fuzzy Logic Toolbox [32] of MATLAB™, completed in Simulink and applied to control the TSK plant model. In system simulation with various reference step changes the mean values of the dynamically auto-tuned parameters are computed - $k_{ei}^m=1.2$, $k_{dy2}^m=1.35$, $k_{dy1}^m=k_{dy2}^m=1.35$, $k_{p1}^m=1.3$, $k_{p2}^m=1.1$. Then the initial gains of the basic two-variable FLC are scaled with the computed mean values and thus fixed and the supervisory FLC disconnected. The off-line control with fixed mean gain values shows the same results, avoids unnecessary parameter time-variation in continuous retuning often provoked by noise effect and allows switching only of the basic FLC – a simple control structure, to the laboratory HVAC system.

4. A Real Time Experimentation and Assessment of System Performance and Energy Efficiency

The plan of the experiments to be carried out on the laboratory HVAC system in Fig.4 is shown in Table 3. The two-variable FLC systems designed and investigated are:

1) a simulated system without supervisory FLC;
2) a simulated system with supervisory FLC;
3) the real time system without supervisory FLC with corrected gains from auto-tuning.

In Table 3 are also given the estimated performance indices – settling time $t_s$, maximal dynamic deviation from reference $\Delta y_m$, energy efficiency according to (1) with respect to relative humidity (channel $i=1$) and temperature (channel $i=2$). The step responses from real time control in MATLAB™ are compared with those from simulation in Fig.8. The global energy efficiency measure (1) is modified to:
**Channel FLC of the basic FLC**

**Fuzzy Unit**

- Normalization
- Fuzzification
- Inference
- Defuzzification

**Knowledge Base**

- Post-processing for PI FLC

**Pre-processing**

- Normalization

**Post-processing**

- Defuzzification
- Knowledge Base

**Performance computation**

- $|\Delta u^o|$
- $|e|$
- $|dy_j/dt|$

**Rules and Inference**

- $k_z = f_z(|e|), k_y = f_y(|y|)$
- $k_p = f_p(|\Delta u^o|)$
- $K'_i = k_e K_e, K'_o = k_o K_o, K'_p = k_p K_p$

**Defuzzification**

$|\Delta u^o|$ $0$ $0.5$ $1.5 k_s m_k b_k$

**Fig. 7 Designed supervisory FLC for a laboratory HVAC system for basic FLC gains auto-tuning**

**Fig. 8 Step responses of relative humidity and temperature of a laboratory HVAC system from simulation and real time control with and without supervisory FLC**
Table 3 Systems performance assessment

<table>
<thead>
<tr>
<th>Reference steps</th>
<th>Systems</th>
<th>Simulated FLC without supervisor</th>
<th>Simulated FLC with supervision</th>
<th>Real time FLC with corrected gains</th>
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<td>Channel</td>
<td>t&lt;sub&gt;s&lt;/sub&gt;, s</td>
<td>y&lt;sub&gt;m&lt;/sub&gt;</td>
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<td>y1-Rh</td>
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<td>700</td>
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<td>y1-Temperature</td>
<td>1200</td>
<td>0.05</td>
<td>0</td>
</tr>
<tr>
<td>3</td>
<td>y2-Rh</td>
<td>300</td>
<td>0.4</td>
<td>250</td>
</tr>
<tr>
<td>3</td>
<td>y2-Temperature</td>
<td>2500</td>
<td>0.4</td>
<td>2400</td>
</tr>
<tr>
<td>3</td>
<td>y1-Rh</td>
<td>400</td>
<td>0.5</td>
<td>200</td>
</tr>
<tr>
<td>3</td>
<td>y2-Temperature</td>
<td>2500</td>
<td>0.3</td>
<td>2400</td>
</tr>
</tbody>
</table>

for all 3 systems

\[ \Sigma(t<sub>s</sub>)^p=23910, \Sigma(y<sub>m</sub>)^p=6.55 \]

<table>
<thead>
<tr>
<th>Total measures</th>
<th>Basis for improvement</th>
<th>18% better</th>
<th>46% better</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \Sigma(U)^p=146.10^4 ), ( \Sigma(</td>
<td>y&lt;sub&gt;m&lt;/sub&gt;</td>
<td>)^p=3 )</td>
<td></td>
</tr>
</tbody>
</table>

\[ (I)^p = \frac{U<sup>p</sup>}{\sum_{p=1}^{3} (U<sup>p</sup>)^p} + \frac{t<sup>p</sup>}{\sum_{p=1}^{3} (t<sub>s</sub>)^p} + \frac{|y<sub>m</sub>|^p}{\sum_{p=1}^{3} (|y<sub>m</sub>|)^p}, \tag{2} \]

where \( k=1÷4 \) is the number of the step response (experiment), \( p=1÷3 \) – the number of the system (1 - without supervisor, 2 - with supervisor, 3 - the real time controlled system without supervisor with normalization and post-processing gains scaled with the mean of the correction from the supervisor, \( (U)^p=\sum_{i=1}^{2} (\sum_{k=1}^{4} U<sup>k</sup>)^p \), \( (t<sub>s</sub>)^p=\sum_{i=1}^{2} (\sum_{k=1}^{4} t<sub>s</sub><sup>k</sup>)^p \) and \( (|y<sub>m</sub>|)^p=\sum_{i=1}^{2} (\sum_{k=1}^{4} |y<sub>m</sub>|<sup>k</sup>)^p \) are the total for the corresponding system control effort, settling time and maximal dynamic deviation from reference. The less \((I)^p\) is the more energy efficient the system is.

According to Table 3 the most energy efficient is the real time controlled system \((p=3)\). Assuming the two-variable FLC without supervision as a basis for comparison, it can be concluded that the introduction of the supervisor leads to 18% reduction of \( I \) and the real time control – 46% reduction of \( I \). This is mainly due to fixing the corrections and the avoidance of continuous unnecessary tuning often due to random influences. Besides, the control structure is simplified. Therefore, this FLC will be further completed in an industrial programmable logic controller [16].

5. Conclusion

The main contributions, described in this paper, are the following.

A laboratory two-variable HVAC plant is developed, supplied with the necessary equipment for control via a DAQ by a Simulink controller in MATLAB™ real time or by industrial PLC. It allows controlling climate comfort by stabilization of chamber temperature and humidity.

A fuzzy PI two-variable controller with a supervisory FLC is designed from robust stability, performance and energy efficiency criteria and tested in real time control of the laboratory HVAC. A simplification is suggested for keeping fixed the corrected by mean values from auto-tuning gains.

The experimentation of the closed loop system with fixed corrected gains in realistic environment shows a decrease in energy consumption of settling time and maximal dynamic
deviation from reference in comparison to other types of control used – two-variable PI FLC without supervisory FLC and with continuous supervisory auto-tuning.

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**References**


