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FUZZY CONTROL SYSTEMS FOR THERMAL PROCESSES: SYNTHESIS, DESIGN AND IMPLEMENTATION

Lyupco N. ANTOVSKI[1] **Mile J. STANKOVSKI** [2]

Tatyana D. K. GUGULOVSKA[3] **Georgi M. DIMIROVSKI** [4]

[1]PMF Institute of Informatics, SS Cyril and Methodius Univ., 1000–Skopje, R.of Macedonia
[2,3]FEE Institute of ASE, SS Cyril and Methodius University, 1000–Skopje, R. of Macedonia
[4]FE Department of Computer Eng., Dogus University, 34722–Kadikoy/IST, Turkey, and
FEE Institute of ASE, SS Cyril and Methodius University, 1000–Skopje, R. Macedonia

[1]E-mail: anto@ii.edu.mk [2]E-mail: milestk@etf.ukim.edu.mk
[3]E-mail: tanjakg@etf.ukim.edu.mk [4]E-mail: gdimirovski@dogus.edu.tr

ABSTRACT

A completed case study on fuzzy logic control of thermal processes has been carried out using a professional laboratory oven for industrial purpose as an experimental test rig. It involved system engineering design analysis, control synthesis, and implementation as well as application software and signal interface design and development. The resulting expertise and lessons learned are reported in this contribution. The structure of PD type of fuzzy logic controllers is closely discussed along with synthesis issues of membership functions and knowledge rule base. Special software was developed using Microsoft Visual Studio, C++ and Visual basic for GUI for a standard PC platform. The application software designed and implemented has four modules: FIS editor, Rule Editor, Membership Function Editor and Fuzzy Controller with Rule Viewer. Quality and performance of the overall fuzzy process control system have been investigated and validated to fulfill the required quality specifications.

Keywords: *Application software development, fuzzy control synthesis, design, implementation, industrial laboratory oven, thermal processes.*

I. INTRODUCTION

It is well known that thermal processes, regardless technological object (compartmental one, typically) in which these take place, possess inherent nonlinearity and time delay phenomena, and often time-varying parameters too [9], [28], [29]. With regard to their dynamics, however, these are low-frequency objects with natural steady-state equilibrium and non-oscillatory transients [6], [27], [29]; in turn, about the operating equilibrium, it may well be approximated by first or second-order plus pure delay representation model dynamics [27]. Nonetheless, requirements on modern industrial automatic control applications impose simultaneously ever greater accuracy and faster response times [2], [3].

On the other hand, industrial process control practice demonstrates considerable work time may be required for system re-design as well as implementation renewal in the course of regular maintenance of the

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existing plant installations. Yet, for obvious reasons, this work has to be reduced to the bare minimum [2]. Thus, in practice, stringent system engineering specifications are imposed involving to meet some opposite operating effects on the grounds of their balanced engineering trade-offs. Hence, both the science of system synthesis and the art of system engineering design have to be employed to the full. It appears that fuzzy logic controllers, in terms of both efficiency and cost-effectiveness, offer perhaps the best alternative to thermal process control applications [8], [9]. This complies with the arguments for as put forward by E. P. Mamdani in [25].

In this article, a innovative and successful complete case study design and implementation of fuzzy logic control of thermal processes via a prototype, electrically powered, industrial laboratory oven is reported. It has been carried out at FEE-ASE Institute Skopje. This research project was accomplished following the respective developments in both scientific knowledge and system engineering design and implementation in fuzzy systems and control since 1995 [7]. Our applied oriented research has made full use of L.A. Zadeh's seminal works [34]-[36] on theory of fuzzy sets [5], [15], [20] and approximate reasoning [37]-[39], and in the subsequent developments of fuzzy systems, fuzzy control and identification, and linguistic based synthesis, e.g., see [4], [6], [10], [13], [21]-[24], [30]-[32]. Scientifically, this is a matured field nowadays [17], [18], [33], but not yet in terms of system engineering design [1], [14], [26], [32]. We have found practically useful scientific clarifications of problems involved in applications oriented representation models of fuzzy controllers found in [11], [30], [32] as well as in the in-depth studies in [7], [10], [33], which are highlighted in this article via the respective comments and remarks.

The reported presentation in this article is organized as follows. In the next Section II, in its three subsections, fuzzy logic control systems from the perspective of recent findings on controlling thermal process are discussed, and details on design development a fuzzy-logic controlled prototype oven (a kind of test rig) is presented. The subsequent Section III gives a presentation of further essential details on fuzzy logic controller design, the overall system engineering, and on associated experimental investigation. Also, there are presented the performance achieved and validation of the designed fuzzy logic controller (FLC), via its implementation, by making use of results of both the software design and of the operation of prototype oven. Section IV presents a relevant discussion on the potential application of the resulting FLC to gas-fired, high-power, multi-zonal industrial furnaces. Then conclusion and references follow thereafter.

2. ON INDUSTRIAL FUZZY CONTROL SYSTEMS FOR THERMAL PLANTS

As pointed out in the introduction, thermal processes and plants possess inherent nonlinearity and time delay phenomena; time-varying parameters may or may not be induced by load variations. Temperature dynamics of these plants to be controlled, even in cases of multi-compartmental ones (e.g., multi-zonal industrial furnaces), is a low-frequency one having natural steady-state equilibrium and non-oscillatory transients. In turn, about the operating equilibrium, it may well be approximated by well-known Küpfmüller-Strejc first or (seldom) second-order plus pure delay representation model, and by and large this is correct in per compartment consideration [6], [9], [27]. In the present case study on prototype oven, controlled plant is a single-compartmental one.

A control system engineering design employing a fuzzy controller in regulatory mode for industrial process plants, except for the controller (block 2 in Figure 1), belongs to the standard *single-input-single-output* (SISO) computer control systems [2], [3]. The architecture of these systems is the basic scheme of an industrial, automatic, process control system, which is depicted in Figure 1.

The two just presented arguments above do represent premises of systems engineering technology as well as these set up all relevant constraints in this case study.

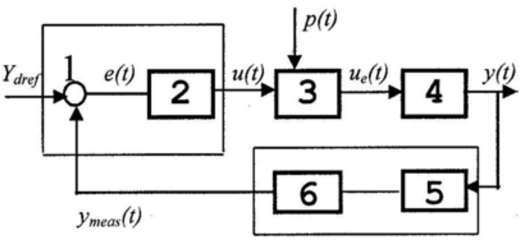

Fig. 1 Architecture of industrial computer process control systems employed for the prototype, electrically powered, oven plant.

In thermal process control, such as in the prototype oven plant of concern in here, controlling process is carried on the grounds of the on-line, real-time measured temperature process variable. In particular, engineering design reported here makes use of the following units:

1. The Control Error Unit where real-time comparison of the reference (desired equilibrium state, e.g. of oven temperature) and the actual real- process variable (temperature) of the controlled (thermal) process in the plant is carried out.

2. The Controller – in this case study, a fuzzy-logic control computation subsystem.

3. The Actuator Unit – the electrical power amplifier and heater in this case study.

4. The Controlled Process Plant – in this case study, the industrial laboratory oven in ASE Lab test-rig with implemented temperature sensor for on-line real-time measurements.

5. The Information Signal Element – a temperature sensor, in this case study a thermocouple.

6. The Information Signal Transducer – a milivolt-to-volt amplifier and filter in this case study.

Consequently, variables that are indicated in Figure 1 represent:

$Y_{d\,ref}$ - the desired reference temperature, converted into appropriate electrical signal acceptable for computer process controller implemented on a standard Pentium PC with standard interface card unit.

$y_{meas}(t)$ - the real temperature in the furnace, converted into electrical signal that is linearized, filtered and amplified.

$y(t)$ – plant process temperature (in degrees Cellsius or Kelvin, alternatively).

$e(t) = Y_{d\,ref} - y_{meas}(t)$ - control error signal, defined as the difference between the desired and the measured actual temperature in the furnace.

$u(t)$ - voltage control signal (DC) corresponding to defuzzified FLC output.

$u_e(t)$ – controlling output from the executive control unit, voltage signal (AC 0-200 V).

$p(t)$ – variable representing the power supply of the executive control unit (220 V, 50 Hz) in the overall system.

2.1. On Structure, Design, and Operation of Fuzzy Logic Controllers

Details of real-world operation of process fuzzy controller in terms of repeated cycles four main tact-steps is well known (e.g., see [7], [10], [11], [21]). The real-time process measurements that represent relevant conditions of the control process, the crisp process values, are singleton fuzzified and converted into appropriate fuzzy sets to capture measurement and process uncertainties. Fuzzified measurements are then used by the inference engine to evaluate the control rules stored in the fuzzy rule knowledge base. The outcome of this evaluation is a fuzzy set, or several ones, defined on the discourse universe of possible actions, which is converted into a single value, a scalar crisp or a vector of crisp values, that makes up the best representative of the fuzzy logic inferred set. This defuzzified, and subsequently denormalized, value represents the current action undertaken by the fuzzy controller and executed by executive control unit in every operational cycle.

The above descriptive discussion is illustrated in Figure 2. For the sake of clarity, variables are qualitatively characterized by three linguistic labels only, denoted N (negative), Z (zero), and P (positive), which are represented by the respective fuzzy subsets.

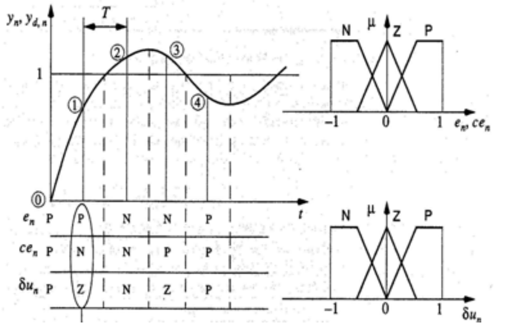

Fig. 2. Instantaneous operating response of an FLC law,
$\delta u_n = FLC\ (e_n, ce_n) = g_{FLC}\ (e(t_n), \delta e(t_n))$
employing the minimum of 3 linguistic labels.

In control applications to thermal plants and other process plants of mass and energy transfer and transformation these three are not sufficient [6], [9], [25]. The algorithmic system structure of the generic fuzzy controller (note block 2 in Figure 1) is depicted in Figure 3, however. This structure also provides the detail on control computations involved in generic fuzzy logic controllers in general.

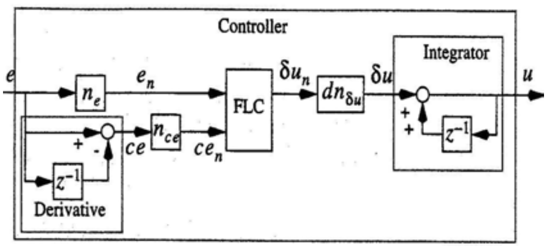

Fig. 3 Algorithmic system architecture of the generic fuzzy controller, represented by block 2 in Figure 1.

Thus, in general, a generic fuzzy logic controller (FLC) consists of the following modules: Normalization module; Fuzzification module; Fuzzy inference engine and associated knowledge rule base; Defuzzification module; and Denormalization module. The interconnections and information flow among these modules and the interface with controlled process are shown in Figure 4.

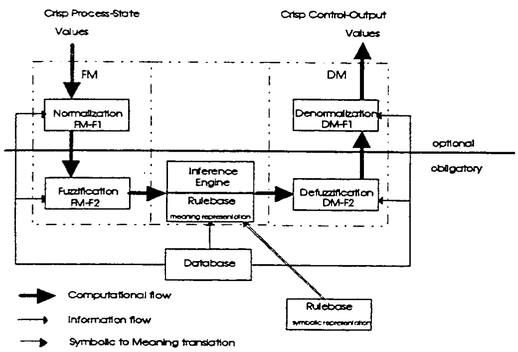

Fig. 4 Architecture of industrial fuzzy logic controller design employed for the prototype oven plant.

In a rather similar manner, according to the modular structure of FLC's, the respective system engineering design and synthesis of the fuzzy controller for thermal processes involves certain similar steps. From pragmatic point of view, typically FLC system engineering design involves practical steps as described in the sequel.

Step 1. After identifying the current *error signal* e, the difference between the actual value of the controlled temperature and its desired value, and the change-in-error signal $\delta e = ce$ corresponding to the current derivative & as the relevant respective input variables to fuzzy system based controller algorithm, the update computed, defuzzified, controller output variable u is to be converted into output voltage (as a relevant physical variable), certain selection of meaningful linguistic states for each variable must be accomplished. For high quality control around the target value of the temperature, a fuzzy controller employing seven linguistic state values for each input and output variable has been found to be instrumental; linguistic values are as follows: NL-*negative large;* NM-*negative medium;* NS-*negative small;* AZ-*approximately zero;* PS-*positive small;* PM-*positive medium;* PL-*positive large.*

Remark 1: Due to natural features of thermal processes, in general, and in industrial furnaces in particular, [8], [9], the recommendation for less linguistic labels (fuzzy subsets) than the above recommended ones is not entirely correct if a high quality performance of the controlled process is to be achieved.

Step 2. After the normalization process, where input crisp values are transformed into values acceptable for the universe of discourse of the fuzzy controller algorithm, the fuzzification process follows in accordance to the fuzzy rules in controller's knowledge base.

Step 3. In this step the knowledge emanating from the controlled process and pertinent to the given control problem is formulated in terms of a set of *fuzzy inference rules*.

Remark 2: For the initial design in the case of thermal processes as well as in other real-world industrial cases, the principle of determining the relevant inference rules from the knowledge of the experienced human operator [13], [25], [31] is strongly recommended.

The inference rules have the canonical if/then structure, of course. Since in this fuzzy system based controller design each input variable has seven linguistic values characterizing the state of processed information on control problem, the total number of possible non-conflicting fuzzy inference rules is 49. Conveniently, Figure 5 represents the rules in a matrix form of the designed FLC fuzzy-rule knowledge base.

The first step in the choice of controlled process and control-output variables consists of the determination of the type of fuzzy knowledge based controller. Because of *the characteristic features of thermal processes and the category of knowledge due to the human operators, the use PD type of fuzzy controller is to be preferred* in thermal plants. In short, the PD fuzzy controller is a *multi-valued logic emulation* of the traditional PD-law industrial controllers (e.g. see, [10], [17], [19]. Fuzzy-rule knowledge based controller of PD type has the linguistic representation of the rules in the general form as described below in terms of If-Then rules [36], [39]:

IF e is <property symbol> AND Δe is <property symbol> THEN u is <property symbol>. (1)

This way control output is directly placed in a most appropriate correlation with the fuzzy information on the real-time evolution of control error and its trend of change as they happen in the actual plant. With the choice of seven linguistic state labels for each of the three variables invloved, identified in Step 1, the matrix representation of the fuzzy rule based PD type controller algorithm for thermal processes is given in Figure 5.

E\Δ	NB	NM	NS	ZO	PSS	PMM	PBO
NB	NB	NBB	NB	NB	NM	NS	ZO
NMM	NBB	NB	NB	NSM	NS	ZO	PS
NS	NB	NB	NSM	NS	ZO	PS	PM
ZO	NB	NM	NS	ZO	PS	PM	PB
PS	PM	NS	ZO	PS	PM	PB	PB
PMM	NS	ZO	PS	PM	PB	PB	PB
PB	ZO	PS	PM	PB	PB	PB	PB

G00
G1
G2
G3
G4

Fig. 5 The resulting knowledge rule base for the designed PD-type fuzzy logic controller

$$\delta u_n = FLC\ (e_n, \delta e_n)\ ,\ e_n \in E\ ,\ \delta e_n \in \Delta\ .$$

The type of PD-like fuzzy control algorithm is preferred because of facilitating speedy response of the rather inertial thermal processes. Nonetheless similarly, a PI- or PID-like fuzzy control algorithm can be designed. Of course, the respective knowledge bases shall not be the same [7], [10].

Now, a set of short but important pragmatic comments on groups of fuzzy rules in the designed knowledge base, Figure 5, is presented below. These have emanated from the present systems engineering case study on fuzzy logic control design and implementation to the prototype oven and the preliminary analysis on its potential application to multi-zonal industrial furnaces.

These pragmatic comments are presented in the following groups (also see Figure 5) as appropriate.

Group zero, G0: It presents the current value that is close to the target desired value of the control temperature. The control output u is condensed around the values of sustaining the current temperature y.

Group one, G1: The output process valuable y is greater than reference value. Because the derivative of error is positive, y is moving towards the reference point with controlled speed.

Group two, G2: In this group y is moving away from the reference point. With the positive control the aim is to change the direction of changes towards accomplishing the reference point.

Group three, G3: Because of the local behaviour of e and δe, y starts to move towards the reference point. The main goal of the control is to reach and maintain the reference point (regulatory mode) considerably fast and without overshoot.

Group four, G4: In this case y is tending away from the reference point. The negative control value is aimed to change significantly the direction of the change of y.

Remark 3: Because it is always desirable to achieve fine control around the target reference temperature without or with negligible limit-cycle oscillations in the steady state, a wider range of linguistic variables and values have to be employed. This way a rough but satisfactory control in the presence of large error is achieved, and in the vicinity of the target reference temperature refined controlling actions are accomplished. During the design of the inference engine the set of rules have been found to fulfill the conditions of completeness, consistency, and continuity [7], [17], [32], [33]. The completeness is achieved by the choice of combination of input values that results in an appropriate set of output values. The representation of the rule base in matrix form prevents from inconsistency in the rule consequence, which is manageable task for the class of thermal plants employing SISO control systems. With neighbouring rules that do not have conflicting intersections, the continuity of the rule set is achieved too.

Step 4. The inference engine is based on individual-rule based inference. Each single rule is individually fired with the fuzzified crisp input. This way the same number of clipped fuzzy sets is obtained for the output as the number of rules in the base. Finally the combination of those fuzzy sets into one overall fuzzy

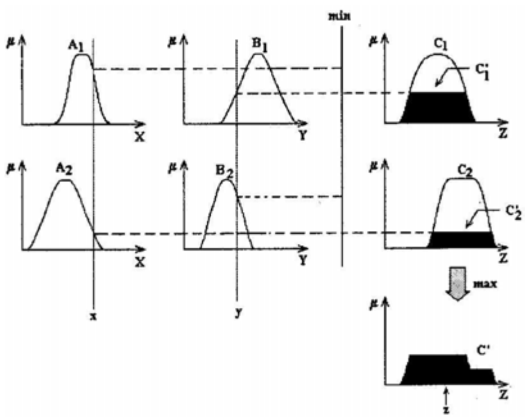

Fig. 6 An illustration of Mamdani's fuzzy logic inference employed; X and Y are support fuzzy sets to error and change-in-error, Z is support fuzzy set to inferred control output.

set is made using Mamdani's implication [22], [24] with individual-rule based inference (see Figure 6).

Step 5. In the last step of the designed process a suitable defuzzifacation method is selected. To convert each conclusion obtained by the inference engine, expressed in terms of fuzzy set, to a single real number an appropriate defuzzification method has to be chosen. There are several defuzzification methods that lead towards correct solution. All methods suggested in the literature (centre of area; centre of sums; height; centre of largest area; first of maxima; middle of maxima) are based on a rationality.

Remark 4: Because it is always desirable to accomplish the maximum accuracy results, the centre of area defuzzification method for the fuzzy control of thermal processes is recommended (see also [8]. This has been also experimentally validated at ASE Laboratory test rig too. For the computing implementation, the just discussed method is represented by means of the following formula:

$$u_n{}^* = \frac{\sum_{i=1}^{l} u_i \cdot \max_k \mu_{CLU^{(K)}}(u_i)}{\sum_{i=1}^{l} \max_k \mu_{CLU^{(K)}}(u_i)} . \qquad (2)$$

According to the experience gained, it may well be argued in favor of this defuzzification method for process control applications. What matters indeed is that this is the most realistic method of defuzzification for industrial processes, and for thermal ones in particular. For, the defuzzified crisp value is the centre of gravity of the clipped fuzzy subsets it works well even with no overlapping taken into account.

Remark 5: Lastly but not least, it is emphasized that an almost ideal fuzzy partitions of the respective domains of error and change-in-error inputs, and of control output has to be elaborated.

In here, no further analytical detail on fuzzy inference systems and fuzzy logic controllers is given because of the vast literature is already available. The interested reader is recommended to see [33] in particular.

2.2. Engineering Design Considerations for the Interface Process-Controller

In control system engineering design, the aspect of interfacing the real-world process to be controlled to the controller must be treated with care, because once coupled these created a system structure with entirely novel behaviour features and properties. In this subsection, a few pragmatic issues are pointed out. These are believed to be important whenever the goal is a full-scale systems engineering project of applied fuzzy logic control. Of course, these are discussed on the grounds and in the context of ASE Lab test-rig implementation, which still is an industrial laboratory oven, electrically powered and used for the purpose of various quality control tasks in industry.

2.2.1. On the Actuator Unit Interface

The amplifier of electric power is actuator that has the goal of changing the flow of electric energy through the process-controlled unit to achieve the desired algorithm of control. The power that is delivered to the oven can be controlled with the change of the effective value of the voltage of the furnace heater.

There exist three types of well-known control methods for thyristor devices: periodic on/off control; phase control; and pulse-wide control. In ASE Lab project the phase control principle has been implemented; for industrial scale plants, however, other control principles should be observed within the respective technology context.

The power of the heater is regulated with the change of the angle of activity of the tyristors implemented in the electric power amplifier. The amplifier has the following characteristics: the input is DC voltage in the range 0-10 V obtained from the AD/DA computer card. The output is AC voltage in the range 0-220 V, 50 Hz. The transfer function, considering the nature of the amplifier, is a non-linear one. This contributes to potential imprecision in controlling the thermal process that has be compensated by employing the relevant characteristics of the fuzzy controller.

2.2.2 On Transducer Unit Design

Transducer unit is consisted of sensor and transducer. The sensor is thermocouple of K type built out of Chromel and Alumel. It is used in the range of 0-1260°C. Thermocouple is temperature transducer that is based on the property when two metals are connected, among the ends of the connection a potential difference is generated. It is in a correlation with the difference of the temperature between the real temperature and the referent temperature.

The transducer is represented with the circuit for linearization, filtration and amplifying of the electrical signal. It implements the integrated circuit AD597, monolithic set point controller optimized for high temperatures, as in the systems of the control of temperature in the furnaces. This transducer can operate in the range of the temperatures 200-1250°C. It has precision of ±4°C when linearized for temperatures around 175°C; similarly, it can be linearized for other operating temperature points. The output signal from the transducer is voltage in the range 0-10 V used as an input in the AD/DA card of the computer and then consequently as an input in a fuzzy controller.

It should be noted that the high ones in the range of operating temperatures, pointed out above, are typical in metals processing industries, where high-power gas or gas/oil powered multi-zonal furnaces are used. Of course, then the sensing element, either thermocouple or resistor-bridge sensor, shall not be exactly the same one as in this oven plant. This issue is of importance for the discussion presented in Section IV.

2.3. On Stability Considerations for FLC Control System Design

As a rule, industrial control systems must possess stabile bahaviour ensuring command reference to be reached and retained in a finite time, which implies that desired operational equilibrium of controlled plant has been implemented. Usually, it is referred to as *practical stability* and specified in terms of constraints on the allowable: overshoot – maximum instantaneous control error; damped oscillatory transients – maximum settling time; and steady-state error – minimum value of constant or limit-cycling offset. Nonetheless, prerequisite for achieving this is the closed-loop asymptotic stability implying fast convergence of control error to zero equilibrium. Theoretically, the only generally applicable and valid method is *Laypunov's direct or second method* of nonlinear stability analysis [16], and if needed then iterative control redesign is carried out.

As for the closed-loop asymptotic stability in the case of thermal plants, recall here the characteristic features of their temperature dynamics, outlined earlier in this article. Since the overall system is a SISO control system, asymptotic stability may well be established by using combined approximation with sector nonlinearity plus second-order linear dynamics. In qualitative terms, the closed-loop control system is readily seen to be well approximated as being dominated by a second-order error dynamics (also, see Figure 2).

Furthermore, we point out that the well known Aizeramn's and Kalman's conjectures [12], [16] for nonlinear SISO control systems apply in this case study. This is due to the facts on the input-output map of fuzzy logic controller equivalence to a multi-level relay control law, and on the nature of thermal dynamics in ovens and furnaces possessing natural steady states and non-oscillatory steady states. The desired, FLC forced, temperature equilibrium in closed-loop, however, may induce transient oscillations, albeit highly damped, and negligible steady-state limit cycling.

Consequently, stability analysis can be carried out by any of the known methods for nonlinear control systems analysis. That is, it can be done either via phase-plane [1], [14] or Lyapunov function synthesis [7], [16] (e.g., Laypunov's method employing Lure type Lyapunov functions), or by using circle criterion [26] based on Popov's theorem [12]. To complete this line of argument we present below an outline of the analysis in the discrete-time systems setting, which is relevant for implementation by means of computer process control systems.

Firstly, the relevant version for discrete-time systems of the well known Lyapunov theorem [12], [16] is recalled in the context of the dynamics of control error signal, $e = e(t_n) = e_n$ and $\delta e(t_n) = ce_n$ in computer control systems.

Theorem. The equilibrium state in the origin, $\vec{e}^{e} = \vec{0}$, of a dynamic system $\vec{e}_{n+1} = \vec{f}(e_n)$ is stable if there exists an associated Lyapunov function, $V = V(\vec{e})$, such that the inequality $V(\vec{e}_{n+1}) - V(\vec{e}_n) \leq 0$ is fulfilled along the trajectories of system evolution.

In the considered FLC control systems, the following representation model of discrete dynamics

$$\vec{e}_{n+1} = \vec{f}(\vec{e}_n) + g(\vec{e}_n)u_n, \quad (3)$$

where

$$\left\|\vec{f}(\vec{e}_n)\right\| \leq F\left\|\vec{e}_n\right\|, \left|g(\vec{e}_n)\right| \leq G, \quad F > 0, G > 0 \quad (4)$$

for some suitable constants F and G, can be adopted. Fuzzy rule control law can be represented in the form

$$IF\ e_n\ is\ \widetilde{A}_l\ AND\ ce_n\ is\ \widetilde{B}_l\ THEN\ u_n\ is\ \widetilde{C}_l, \quad (5)$$

where $\{\widetilde{A}_l\}$, $\{\widetilde{B}_l\}$, $\{\widetilde{C}_l\}$ are collections of fuzzy subsets defined over the domains of definition of e, δe, u, respectively.

Following an appropriate elaboration, it may be assumed that these collections of fuzzy subsets create *nearly ideal fuzzy partitions* [33] of their respective domains, which is the case the present case study. Similarly, it may be assumed

$\sum_l \mu_{A_l}(e) \cong 1$, $\sum_l \mu_{B_l}(ce) \cong 1$,

$\sum_l \mu_{C_l}(u) \cong 1$.

Then, on adopting shortened notation as $\mu_l \hat{=} \mu_{A_l}(e_k)$ and $\mu_l \hat{=} \mu_{B_l}(e_k)$ the following relationships

$$\mu_l + \mu_{l+1} \cong 1 + \delta\mu_l \quad (6)$$

among consecutive fuzzy subsets of the inputs are noticed to hold. Moreover, on the grounds of control defuzzification formula (2), controller output can be represented in the form

$$u_n = \left(\sum_{i=1}^{l} u_i \cdot K_l^u\right) \Bigg/ \left(\sum_{i=1}^{l} K_l^u\right) \quad (7)$$

with $\max_k \mu_{CLU^{(K)}}(u_i) = K_l^u$ and summations over all applicable rules. It follows at once then that there exist an upper bound

$$k_{\max} = \max_l K_l^u > 0 \quad (8)$$

that covers all relationships between collections of input and output fuzzy subsets as seen via center and/or center-of-gravity values of $\{\tilde{A}_l\}$ and $\{\tilde{C}_l\}$. That is for all $U_l = K_l^u E_l$ $l = 1, 2, \ldots$; furthermore, this implies that it is also valid $\Delta E_l = \delta E_l e_n$ and $\delta K_l^u = \Delta K_l / K_l$ where $\Delta E_l = E_{l+1} - E_l$ and $\Delta K_l = K_{l+1} - K_l$. Similar relationships exist with respect to fuzzy subsets of change-in-error, of course.

Since triangular membership functions are employed in this fuzzy logic controller design, these readily possess the LR-parameterization. Therefore

$$E_l = e_n - R_l^{-1}(\mu_{A_l}(e_k)),$$

$$E_{l+1} = e_n + L_{l+1}^{-1}(\mu_{A_{l+1}}(e_k)),$$

or, in the shortened notation,

$$E_l = e_n - R_l^{-1}(\mu_l), \quad (9a)$$

$$E_{l+1} = e_n + L_{l+1}^{-1}(\mu_{l+1}). \quad (9b)$$

Hence, the analysis when e_n traverses between E_l and E_{l+1} within $\{\tilde{A}_l\}$ shows that

$$\mu_{l+1} K_{l+1} L_{l+1}^{-1}(\mu_{l+1}) - \mu_l K_l R_l^{-1}(\mu_l) \cong$$
$$\cong \delta\mu_l (1 + \Delta K_l / K_l) \Delta E_l K_l. \quad (10)$$

On the other hand, within the realm of the LR parameterizations in fuzzy sets [15], via expansion of Eq. (7) it can be derived:

$$u_n \cong K_l e_n + \frac{K_{l+1} - K_l}{\mu_{l+1} + \mu_l} e_n +$$
$$+ \frac{\mu_{l+1} K_{l+1} L_{l+1}^{-1}(\mu_{l+1}) - \mu_l K_l R_l^{-1}(\mu_l)}{\mu_{l+1} + \mu_l} \quad (11).$$

By making use in this expansion of the intermediate result pointed out in (10), one can obtain

$$u_n \cong K_l e_n + (1 - \delta\mu_l) \Delta K_l e_n +$$
$$+ (1 - \delta\mu_l)(1 + \delta K_l) \delta\mu_l \Delta E_l K_l \quad (12)$$

or

$$u_n \cong K_l e_n + ((1 - \delta\mu_l) \Delta K_l +$$
$$+ (1 - \delta\mu_l)(1 + \delta K_l) \delta\mu_l \delta E_l K_l) e_n. \quad (13)$$

In turn, Eq. (11) shows the operational gain values of the FLC to be bounded from above as follows:

$$K_l^u = K_l + (1 - \delta\mu_l) \delta K_l +$$
$$+ (1 - \delta\mu_l)(1 + \delta K_l) \delta\mu_l \delta E_l K_l < \quad (14)$$
$$< k_{\max}, \; l = 1, 2, \ldots.$$

Now, note that by calculating norms of Eq. (3) and making use of relationships (4) one can derive:

$$\|\vec{e}_{n+1}\| = \|\vec{f}(\vec{e}_n)\| + |g(\vec{e}_n) u_n| \le$$
$$\le \|\vec{f}(\vec{e}_n)\| + |g(\vec{e}_n)| |u_n| =$$

$$= \left\| \vec{f}(\vec{e}_n) \right\| + \left| g(\vec{e}_n) \right\| \left| k_{\max} e_n \right| \le$$

$$\le F\left| e_n \right| + G\left| k_{\max} e_n \right| = (F + Gk_{\max})e_n \,.$$

Hence, for the stability requirement, effective operational gain of the designed FLC has to be limited according to the inequality

$$k_{\max} \le (1 - F)/G \,, \qquad (15)$$

which is to be satisfied in the course of design trade-offs. It implies that somewhat the control system performance has to be pursued with certain limitation in order to ensure stable operation. And, this has to be done in any implementation oriented case study as the one reported in here.

Let also refer to Figure 7 for thermal process SISO control systems employing FLC. On one hand, it illustrates the derived requirement, and also the interpretation of Popov's theorem via approximate representation of FLC and thermal plant, on the other, as suggested at beginning of this subsection.

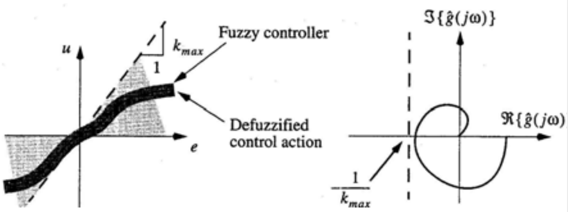

Fig. 7 An illustration of the use of Popov's theorem in SISO fuzzy logic control systems.

It is readily inferred from Figure 7 and all the above analysis on stability consideration that using the circle criterion may be found to be most adequate for fuzzy logic control of thermal processes in SISO control systems. This further supports the applicability of Aizerman's and Kalman's conjectures in this case study. And, so it has been the case. It is true, hwoever, that the above carried analysis is the more rigorous proof.

3. RESULTS: THE APPLICATION SOFTWARE AND PERFORMANCE VALIDATION

During the design, the project was documented in UML (Unified Modelling Language) with the following steps of modelling: Interview; Class diagram; Use case diagram; Activity diagram; State diagram; Component diagram.

The software was developed using Microsoft Visual Studio, especially C++ for the AD/DA card library and calculations, and Visual Basic for GUI (Graphical User Interface). The software package is consisted of the following modules: FIS (Fuzzy Inference System) Editor; Rule Editor; Membership Function Editor; Fuzzy Controller with Rule Viewer. The FIS Editor (Figure 7) makes the heart of the designed fuzzy controller. With its help we built fuzzy controller with desired properties. It has the ability to define the norms for representation of the methods *and, or, implication, and aggregation type of defuzzifacation* methods. With the help of the Rule Editor and the Membership Function Editor, the FIS Editor completely defines a controller ready for action.

The "main action" screen is the window of fuzzy controller with its rule viewer module, which is depicted in Figure 8. It is readily seen that it provides

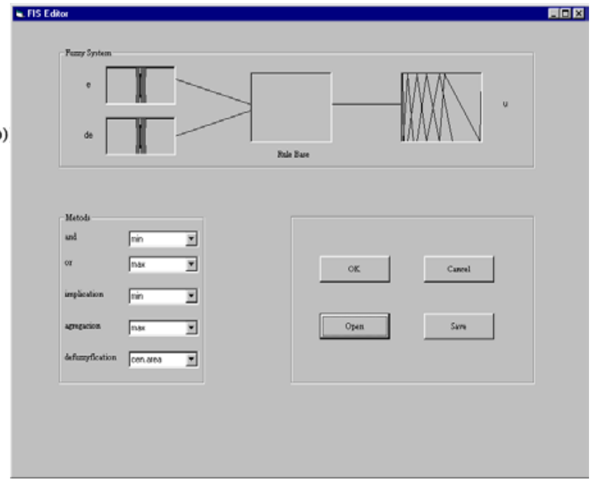

Fig. 8 The window of the editor for designed fuzzy inference system.

thorough insight into fuzzy computations of the controller. Besides other feature properties, it offers to the human operator, designer or user, the possibility of defining the preferred control parameters such as: reference temperature; time window duration; and sampling time period. In addition, the response is saved for further analyses in the course of system engineering design.

On this kind of screen, during the actual performance of controlling process, the main indicating variables of control (actual and reference temperature) are monitored in terms of the crisp and the fuzzy representation of the error, the derivative of the error and the output voltage of the furnace heater (executive control variable). In order to achieve proper real-time monitoring effects, the response of the furnace is also being output in real-time on the screen.

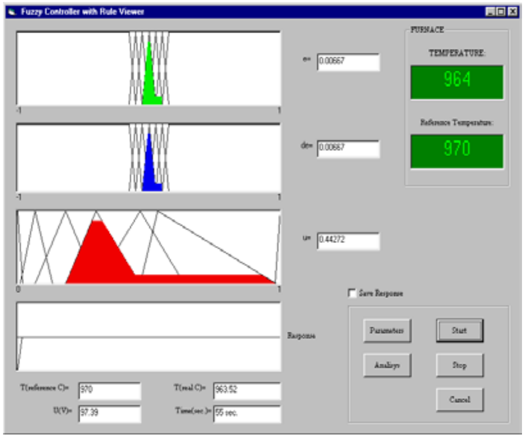

Fig. 9 The window of fuzzy logic controller $\delta u_n = FLC\ (e_n, ce_n) = f(e(t_n), \delta e(t_n))$ with fuzzy rule viewer module.

The window for presenting of the respective operational computations by means of membership functions is given in Figure 9. Hence, the operator has an insight into operational definitions of fuzzy subsets and within the limits of triangular type of membership

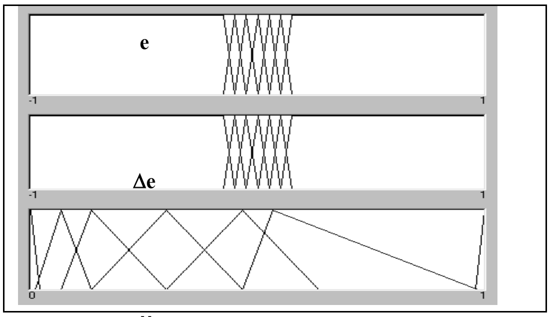

Fig. 10 Presentation of operational fuzzy subsets via respective memberships functions.

functions can make some additional modifications to explore their effects on the control performance. Triangular type of fuzzy membership functions (see also [5], [7], [10]) has been chosen for the sake of computational simplicity. Note that in fuzzy-logic control systems for thermal processes this choice does not imply undesirable side effects

The results of operational testing investigations depended especially on the number, type and position of the membership functions. For the simplicity we used the triangular membership functions with seven fuzzy subsets for each of the input and for the output variables. Within the initial stage of experimental testing, we concluded that in order to achieve more refined control in the vicinity of the desired reference temperature there is a need for more condensed grouping of fuzzy subsets around the zero value for both *error* and *derivative of error* variables. Considering the characteristics of the Actuator Unit, which are non-linear, and the noise in circuits, the output voltage has been represented via positioning the seven fuzzy subsets to compensate for the non-linearity and the noise in the system.

Extensive experimental and operational testing was carried out for the entire set of reference operational temperatures at 100, 200, 250, and 300 °C. In Figure 11, there are shown sample operational responses of the temperature and the output voltage of the heater (executive control unit) obtained in the system with the prototype oven. The characteristic features of the response indicated always a performance close to an almost ideal control.

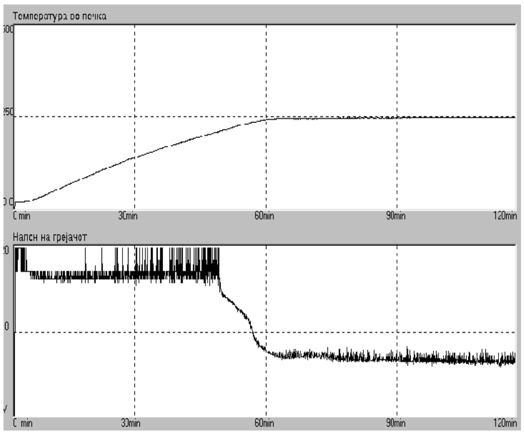

Fig. 11 Initial results in terms of the actual responses of process temperature and heater voltage.

By making use of membership functions involving several fuzzy subsets to obtain the most satisfactory performance (recall previous comments in Section III) there was observed a change in the rule base so as to lower the time needed to desired temperature to reach and remain in the rather local vicinity of the zero-error point without noticeable limit-cycling in the closed loop, hence demonstrating practical stability. Moreover, it has been achieved the response not to overshot the reference temperature more than 1°C, and also calmly to oscillate around the reference temperature with controlled change of 1°C only. Hence stability analysis for asymptotic stability carried out by using approximate representation model for the error dynamics as pointed out in Section III has been validated too.

This way also the need for a modification in the rule base was discovered in order to lower the dominant time constant of the temperature response to the target set-point while avoiding. In turn, due to this modification, implying in linguistic terms 'if *error* is PB and *derivative of error* is NM, then *output voltage* is PB', the achieved system dynamic response is depicted in Figure 12.

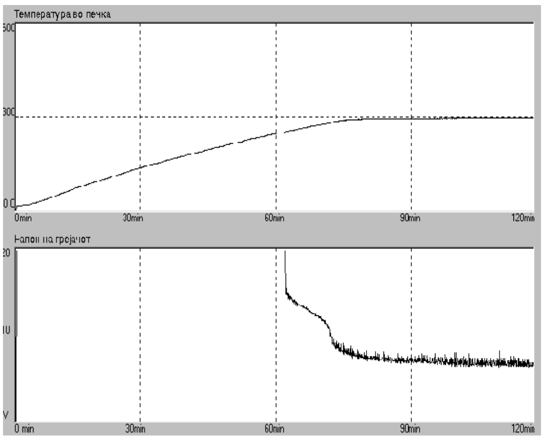

Fig. 12 Actual heater voltage and temperature responses with the modified knowledge base

Experimental investigations with the prototype oven has verified that, with the new modified fuzzy controller, the control system achieves the minimum response time while the overshot is retained to insignificant value of less than 1°C. Also, local oscillation around the desired temperature is confined within the same range of 1°C. Hence, all design specifications have been fulfilled.

4. ON POTENTIAL INDUSTRIAL APPLICATIONS

The gas-fired multi-zonal furnaces represent a technology that is used widely in industrial thermal systems, and the ones employed in metal processing industries have the power of several tens of mega-watts [9]. A schematic of such a real-world 20 MW furnace in FZC "11 Oktomvri", Kumanovo, MK [29] is depicted in Figure 10 below. Without dwelling on details about their construction and controlled operation, it may well be seen from Figure 13 that their overall control involves a supervisory controller (driving command according to desired temperature profile of reheating process) and four zonal control systems in regulatory mode, one for each of the zones [8], [9].

Let put the focus on thermal process control in *a single zone* within this kind of multi-zonal industrial furnaces. It should be noted that the entire system analysis presented in Section II, which emanated from the fuzzy logic control for prototype oven, also applies to the case of one zone. Namely, note the following facts:

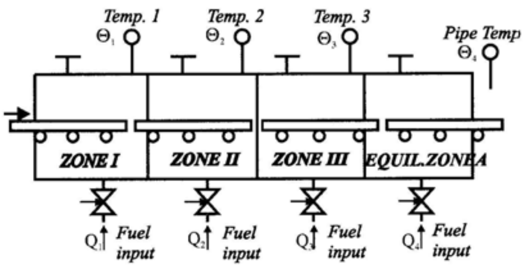

Fig. 13 A schematic of a gas-fired, four-zone industrial furnace with disposition of transducers and actuators for temperature control.

(i) This thermal system exhibits the same essential features of low-frequency process dynamics with natural steady-state equilibrium,
(ii) Sensory subsystem by and large belongs to the same category of technology; and
(iii) Executive control subsystem, although being of entirely different technology, nevertheless possesses rather similar dynamical characteristics due to fast response of gas powered combustion.
Because of these features, in qualitative terms, the error dynamics of local regulatory control system is predominantly of second order. The

qualitative control error dynamics in all four zones is alike.

On the other hand, by its very theoretical essence, the designed fuzzy logic control does not require to make use of a model representation of thermal process to be controlled, except for validating the practical closed-loop stability. Hence the fuzzy logic control design and associated developments (with a different signal interface unit for gas-valve actuators, of course) can be transferred directly to local controls of gas-fired industrial furnaces, albeit some of FLC design parameters may require additional adjustments. This a future project on control technology transfer without any additional basic research.

5. CONCLUSION

The designed fuzzy logic controller applied to prototype oven gives excellent performance in laboratory operating conditions. Therefore these shall deteriorate much in noise-contaminated, factory-floor environment. It should be noted that thermal class processes to be controlled naturally posses steady states. With such quality transient, fast response and steady-state accuracy, fuzzy automatic control becomes reality in the contemporary industrial automation and control systems engineering. Indeed designing fuzzy controls with the use of human experience and intelligence for this class turns out to be a rewarding and pleasant engineering experience.

Even though a comprehensive knowledge gained from experienced human operators promises a good start always, nonetheless it is a challenge to the art of systems engineering on how to overcome the tuning problems via the synthesis appropriate rule knowledge base. The choices available comprise both correct positioning and appropriate number of fuzzy subsets via respective membership functions. Then methods of normalization, denormalisation, fuzzification and defuzzification can contribute to design quality due to their own impacts, respectively, but – it is emphasised – not vice-versa.

The relative simplicity of engineering solutions with fuzzy control concepts is also competitive with regards to the demand for additional human effort, computer resources and difficult mathematical modeling and time consuming computing. Of course, the main advantage of fuzzy controllers remains in the fact that there is no need for an exact or highly sophisticated mathematical representation model of process to be controlled. And, this has again been verified through our investigations in control and automation of thermal processes in industrial furnaces and building structures. There are only a few points of choice that may doubt the simplicity of systems engineering solution.

For thermal processes, fuzzy controllers can be made real-time systems emulating human operator expertise and (to a certain degree) intelligence too, which in case of non-linear time-varying processes is hard or impossible to express through traditional industrial controllers of PID type. Even though power consumption of prototype oven was greater than with PID controller, the response time and transients compensate for this consumption as it was argued in [9]. Hence, it may well be argued that fuzzy logic based controllers are almost naturally suited for controlling thermal processes in all sorts of plants, and can contribute to calm operation of gas/oil fired furnaces with considerable energy savings.

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