ITERATIVE LEARNING IDENTIFICATION AND DESIGN OF INDUSTRIAL FURNACE PROCESS CONTROL

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Abstract: An applications oriented control systems engineering approach for a class of well-posed thermal systems, e.g. industrial furnaces and ovens, that is consistent with most of theoretical results in systems and control sciences has been elaborated and tested in designing controls for several industrial-scale furnaces. It provides a methodology for iterative learning and resolving process identification and control design for multi-variable systems within a discrete convolution framework and using truncated k-time sequence matrices of characteristic input-output modes as well as their characteristic patterns and singular characteristic patterns, starting with standard non-parametric process time-domain models identified under operating conditions. Within computer process control environment and for practical engineering and maintenance reasons, digital implementations are sought in terms of partial steady-state decoupling and two-term laws or combination of certain MIMO and SISO controls. The pusher furnace in Skopje Steelworks is used to illustrate this methodological approach *Copyright © 2000 IFAC.*

Keywords: Industrial control; pseudo-impulse responses; time sequences, fuzzy-Petri-net supervisor; natural input-output operating modes; discrete-time convolution.

1. INTRODUCTION

It may seem a paradox, but all the exact science is dominated by the idea of approximation – Bertrand Russell.

In the sequel, several reasons will demonstrate why we begin this paper by recalling the words of Professor H.H. Rosenbrock [1977, essay in *Automatica 13, p. 390]:* "My own conclusion is that engineering is an art rather than a science, and by saying this I imply a higher, not a lower status". In addition, the systems philosophy framework in which original real-world systems and their conceptual models and mathematical representations (see Sir Bertrand above) in its very should essence be along the thinking that dynamical processes in the real world (below the speed of light), in general, constitute a unique non-separable inter-play of the three fundamental natural quantities of energy, matter and information (Dimirovski and co-workers, 1977, 1979). Moreover, energy and matter are information carriers, but solely information has the impact capacity as to modulate and direct energy and matter.

In turn, this understanding leads always to a successful identification and design experiments though in an iterative way (feedback law). In our case studies on several (now operational) industrial furnaces this is precisely our approach in: (a) how we applied step and PRBS response identification methods for arriving at equivalent furnace representations in the time domain such as k-time truncated sequence matrices (kTSMs), discrete state-equations, discrete-operator transfer functions (Dimirovski and Gough, 1984, 1990): and (b) how we refined them (Gevers, 1997; Porter and Othman, 1990) and also implemented control algorithm improvements (Zhang and co-authors, 1992; Backx, 1993; Stankovski and co-authors, 1999). Also, we believe the essence behind of the problem of so called input-output (I/O) variable pairing is, in fact, the lack of knowledge on the naturally correct ordering of the operational I/O modes of dynamical processes in the time domain – where these actually take place (Dimirovski and co-authors, 1993).

2. ON THE BACKGROUND RESEARCH

2.1. Some Remarks on Industrial Furnaces

Plant constructions and processes designs of large and high-power industrial furnaces (Figs. 1, 2, 3), kilns and ovens have been under both scientific and technologic research since long time ago (Rhine and Tucker, 1991). The design of their control and supervision systems (Ivanoff, 1934; Zeigler and co-authors, 1943) never seized to attract research endeavours because they are essentially multi-input-multi-output (MIMO) multivariable, distributed-parameter, non-linear processes. Moreover, due to energy saving and environment pollution issues, recently it has been considerably intensified (e.g., see Dimirovski and co-authors, 1994).

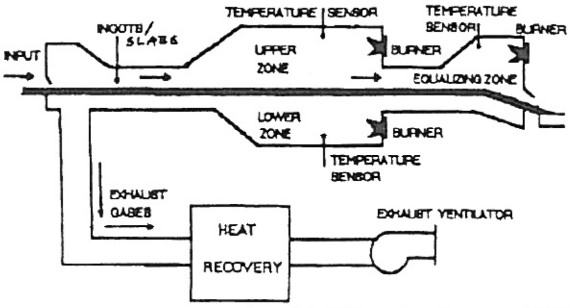

Fig.1 The schematic of a 25 MW pusher furnace RZS at Skopje Steelworks

The real-world operational behaviour of industrial furnaces are characterised by means of a set of features and technical specifications. The most important for the control are the following: three operating regimes low-load and start-up, medium-load and full-load at least; convex I/O control characteristics at operating points; slow and non-linear overall dynamics, but locally linearisable; presence of time-delay and non-minimum phase phenomena; proper sensor allocation distribution as to extract on-line the essential information on operating furnace thermodynamics is crucial; difficult operating and maintenance environment; considerable signal conditioning problem; main controlled variables are the temperatures main controlling variables are energy (fuel) supply/ release, usually, or forced flow of cooled or heated air; furnace pressure is additional controlled variable.

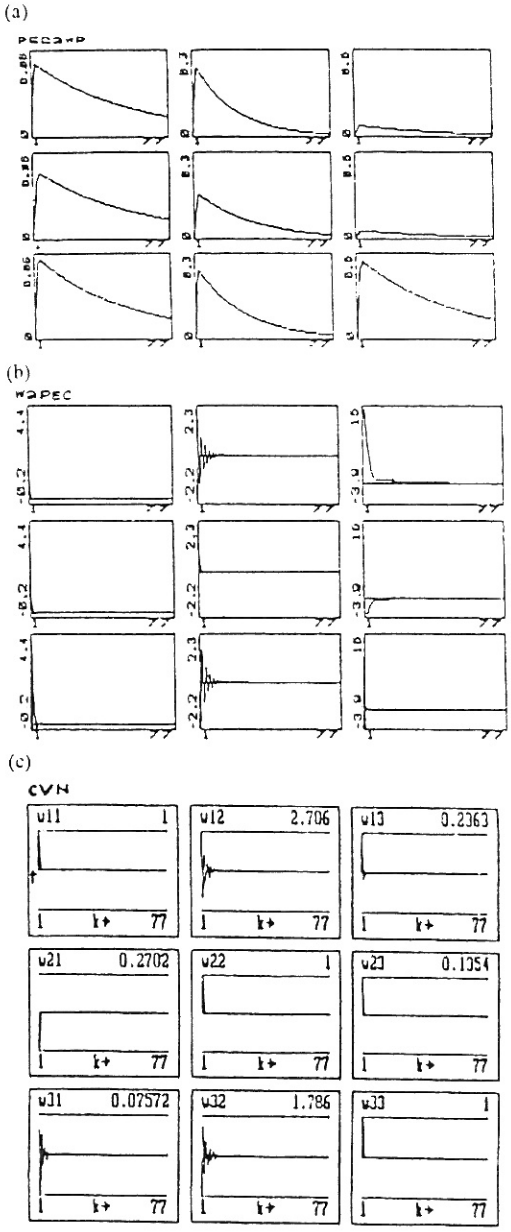

Fig.2. The (3x3) kTSM models for the furnace RZS: (a) operational pseudo-impulse operator $\{g_{ijk}\} = G$; (b) (3x3) characteristic vectors due to interactions; (c) CV normalised version for ordering I/O modes.

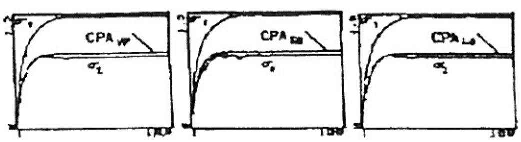

Fig.3. The operational upper and lower bounds on characteristic I/O modes (integrated form) UP EQ LO

For decades their operation, traditionally, has been implemented by human supervision for driving the process from one to another operating regime, in particular - at start and shut-dawn, and by conventional two-term (very seldom the three-term) controls at operating regimes; lastly but not least, safety aspects are crucial (e.g. consider an explosion of a 20 or 25 MW gas/oil fired furnace as in our case-studies). In here, we propose an alternative: two-level system for integrated supervision and control comprising a fuzzy-Petri-net supervisory and a composite MIMO+SISO regulatory controllers.

2.3. Some Remarks on the Background Research

In the course of a number of investigations of industrial MIMO control problems it has become apparent that the so-called input-output variable pairing problem is crucial, and comes, prior to model uncertainty. McAvoy (1984) has elaborated a thorough study. The I/O pairing problem has been tackled using so-called *interaction measures* of which the *relative gain array* (RGA) is the most well-known and introduced first by E.H. Bristol in 1966 and subsequently studied by many authors (just to name a few: A. Niederlinski; W.L. Luyben; G. Mijares, J.D. Cole, N.W. Naugle, H.A. Preisig and C.D. Holland; S. Skogestad and M. Morari; and also Dimirovski, Deskov and Gough and Gough, Ting, Dimirovski and Iliev). Originally it was formulated as a steady-state measure, although it has since been extended to the dynamic case in the frequency domain first, and only then in the time domain (of tangibility to practice engineers) too.

Present authors have long studied the design of process control at the regulatory level in a time-domain discrete convolution framework and its implementation by employing algorithms for computer-controlled plants. Although in here we confine mainly to our own investigations, we also give a short overview on developments. For SISO systems, it has been first introduced by R.C. Dorf (1962) within a linear setting, and then extended to a kind of non-linear setting by R.E. King and D. Williamson (1964). Dorf's approach was extended to time-delay linear SISO processes by N.E. Gough (1973). The extension to MIMO linear case was elaborated by Al-Thiga and Gough (1975, termed Characteristic Pattrens (CPA) method) and by Backx (1987), whereas Dimirovski, Barnett and Gough (1977, 1979) extended it to Lurye-Postnikov non-linear MIMO case. Later Cheng and Desoer (1982) gave full system theortical background for the linear case in terms of discrete-time convolution systems.

In the follow up investigations, more important further contributions on CPA-CVE method are in Gough and Al-Thiga (1985), who studied CPA properties, and in Gough and Mirza (1987), who gave a the general procedure for computing time-domain characteristic I/O modes of discrete MIMO systems, CPA and CVE, including the concept of singular CPAs, which were improved further by Gough, Ting, Deskov, and Dimirovski (1990, 1991, 1992, 1994) and tested in a real-time furnace control problem. The implementations of the underlying design strategy, accomplished by using convolution-based simulation languages, are CBSL and WCBSL (Ting and co-authors, 1990, 1994) and CHIOMOD (Deskov and co-authors, 1991). These results were followed by several applications and some implementations (e.g., Dimirovski and co-authors, 1994; Stankovski and co-authors, 1997) .

Gough and co-authors (1994, 1996) extended these ideas to CPA-CVE decentralised process control, while Dimirovski and co-authors (1994, 1996) to a composite stady-state (SS) decoupled control. Therafter, further development towards a time-domain, iterative design methodology for integrated control and supervision resulted in (Dimirovski 1998; Stankovski and co-authors, 1998, 1999). For industrial furnaces, it is shown in the sequel, a composite MIMO plus one or two SISO controls, integrated by an overall control and supervision system employing a task-oriented supervisory fuzzy-Petri-net controller provide for a rather pragmatic yet quality solution

3. OUTLINE OF THE TWO-LEVEL INTELLIGENT SYSTEM FOR CONTROL AND SUPERVISION

From a system-theoretic and system-engineering points of view and in consistency with developments for MIMO process control of ours, the conceptual setting of our methodology is posed solely in the time domain within the framework of algebra of operators on local spaces (of classes) of functions and/or sequences. In addition, Lurye-Postnikov class of plants also belongs to a left-distributive algebra on extended Banach spaces of p-summable sequences (Dimirovski and co-authors, 1979). It should be noted, however, whereas for scalar system the concept of "gain" is independent of the input, for a MIMO system different directions of the inputs result in different gains, and hence induced matrix norms (Dimirovski - Gough, 1984) are needed.

The two-level conceptual system architecture we propose employs fuzzy-set and Petri-net formalisms at the overall supervisory level, and analytic linear and/or non-linear equations at local controls. Membership functions and universes of discourse, which are most appropriate to operational specifications of envisaged spaces of classes of signals, are found via studying the detail the complex object to be controlled. In industrial plants, most often the event-driven evolution of controlled processes is linked with changing loads and/or some operational specifications. Therefore this discrete-event feature is captured due to fuzzy-Petri-net formalism employed.

3.1. Two-level Architecture for Regulatory Executive Control and Intelligent Supervision

In our previous work, we have studied more closely the system architecture which employs fuzzy-system based control algorithms at its upper, *'qualitative'* or *'non-analytical'*, level of control, and conventional linear and/or affine non-liner controls at its lower levels; the later imply use of *'quantitative'* or *'analytical'* algorithms. It appeared there exist several alternative sub-classes of the same two-level architectures, employing consistently different formalisms at different levels (Dimirovski and co-authors, 1996). In the course of ESF-COSY project of European Science Foundation, our studies have demonstrated that, either if the need for higher autonomy or the complexity of controlled processes requires so, the upper level can be further structured into two layers provided they communicate while competing via compatible languages within the real time of controlled processes. Then, the first layer may implement the task-organising control in terms of fuzzy-rule knowledge base, while the second layer is assigned to generate the co-ordinating command control by using some convenient technique. Moreover, this may be done in terms of static optimisation via conventional or fuzzy-system techniques.

Our two-level system is similar to the known Saridis' solution (1989) with the difference that organising supervisory control level is implemented in terms of a fuzzy-Petri-net controller. This stems from imitating human operator in real-world industrial systems, where most often the supervisory control can be constructed in terms of a production rule knowledge base. Then we have shown in (Dimirovski, 1998), the concept of a fuzzy-Petri-net based supervisory controller provides for considerable advantages. Firstly, task-organising and co-ordinating command controls become two natural layers in a single-level supervisory controller. Secondly, both event-driven and time-driven evolutions are captured in terms of a hybrid but consistent composition of mappings (namely, *linguistic-to-fuzzy-to-event-possibilistic- to-defuzzyfied* commands). And, thirdly, the link of organising and co-ordinating controls becomes a generic one. The feasibility stems from the very essence of fuzzy systems theory, which enables a simultaneous comparative study of tentative spaces of admissible controls (i.e., like antecedent) and of sustainable outputs (i.e., like consequent). Executive regulatory controls may be based either on steady-state decoupled MIMO controls or an appropriate composition of one MIMO and a some SISO controls, or even on fuzzy-neural controls (the latter to appear elsewhere).

3.2. On Fuzzy-Petri-Net Model of FPS for Generating Control Commands via Data Driven Execution

Control functions of the upper, supervisory level regardless of preciseness/ imprecision and certainty/ uncertainty, are known to represent maps of the outside imposed goals and preconditions into or onto appropriate co-ordinated commands to distributed local controls. The dynamics of supervisory control level inevitably involves both time-driven and event-driven evolutions. Hence the language of supervisory control is a hybrid one naturally, and non-analytical. The next step towards the construction an effective mechanism of hierarchically structured supervision and control via fuzzy-Petri-net hybrid systems can be made as follows. Firstly, one has to derive a consistent way to associate *the propositions* in the knowledge base with *the places* in the Petri net by means of a bijective function, as well as to associate *the transitions* with *the degree of truth*. This way, moreover, the Petri-net subsystem itself gets separated from the dynamic process via the concept of data-driven execution of the chaining mechanism of inference. Thus, an improved resolution technique for multi-proposition rules can be implemented.

In brief, for the purpose of this paper, it is essential to note the needs to identify an association of the palaces within Petri network (PN) with the propositions within the fuzzy-rule knowledge base (FKB). This task well resolved by means of the following *bijective function of projection*:

$$\alpha : P \rightarrow PR,\ p_k \rightarrow \alpha(p_k) = pr_k, k = 1,\ldots,K \qquad (3.1)$$

Here, $PR = \{pr_k\}$ is the set of propositions in the FKB, and K is the number of propositions in the FKB. This way, in fact, a projection of the FKB onto the FPN model is performed. In the case when one proposition may appear in different rules within the FKB, a different place in the FPN will be assigned for each effective appearance. This is needed because the rules are characterised by the linguistic value of the variable of truth. The modelling representation is becoming simpler when the same proposition appears in the consequent part of several rules, and the linguistic values of the rules are equal. For, then one place in the FPN solely is assigned to such kind of propositions.

The graphical representation of the FPN is defined in terms of directed arc graphs, within which traditionally circles represent the places while bars represent the transitions within the FPN model. There are permitted in the FPN, however, only directed graphs belonging to the set of graphs A, as defined below

$$A = \bigcup_{t^j \in T} \{ t^j \times O(t^j) \} \cup \{ I(t^j) \times t^j \} \qquad (3.2)$$

In addition, in the next step on needs to define a *function of truth* f_{th} that assigns to each transition $t^j \in T^R$ of the FPN model the linguistic value associated with the corresponding rule R^j :

$$f_{th} : T^R \rightarrow V_l ,\ t^J \rightarrow f(t^J) = \tau^J \qquad (3.3)$$

Here, V_l represents the set of linguistic values of the linguistic variable of truth.

The representation of transitions is much more involved because of the chaining of rules. In the in our representation modelling of our systems, we use the set $T = T^R \cup T^C = \{ t^1 ,\ldots, t^R , t^{R+1} ,\ldots, t^{R+C} \}$. The subset T^R encompasses the rules of the each individual rule within the FKB, and T^C encompasses the rules that are having links between the propositions. Therefore the Petri-net input and output functions are defined on T

$$I : T \rightarrow \phi(P),\ O: T \rightarrow \varphi(P) \qquad (3.4)$$

and this way they assign to each transition a subset of input and output places in the FPN. These functions now may have different interpretations depending on the set T to which they correspond by definition. This is better seen from the relational expressions:

$$\begin{aligned} &\text{IF } t^J \in T^R,\ \forall p_i \in P,\ \forall p_i \in I(t^J) <=> \\ &\qquad <=> \alpha(p_i) \in \textit{Antecedent Part} \text{ of } R^J \\ &\text{IF } t^J \in T^R,\ \forall p_i \in P,\ \forall p_i \in O(t^J) <=> \\ &\qquad <=> \alpha(p_i) \in \textit{Consequent Part} \text{ of } R^J \qquad (3.5) \\ &\text{IF } t^J \in T^C,\ p_i \in I(t^J),\ p_k \in O(t^J) <=> \\ &\qquad <=> \alpha(p_i) \text{ IS } \textit{LINKED WITH } \alpha(p_k). \end{aligned}$$

Consequently, there exist in the FKB a single transition for each of the intermediate variables X_j that are used within the knowledge base rules.

Now, there are easily introduced the concepts of reachability and immediate reachability for places and of causal adjacency for transitions: The later two are of particular importance for proper rule-chaining in the FPN supervisory controller to yield correct multiple links within the FPN model equivalent to the FKB projected onto that FPN, which captures event and task specifications. See (Dimirovski, 1998) for full detail.

4. ON ITERATIVE PROCESS IDENTIFICATION AND EXECUTIVE CONTROL DESIGN

Industrial applications, typically, involve the operational technical specifications of purposive description of aims and procedures of both recommended settings of regulatory and other control functions along with certain terms of pre-conditions and limitations for the supervisory actions. In addition to recorded response time series, these specifications and operator's empirical knowledge too (if available) provide for basic data and knowledge to elaborate event primitives in terms of linguistic and/or hybrid variables, for the supervision level of task-oriented controls, and regulation references for the set-point-oriented controls.

These facts create an *appealing incentive* to study *the two-level system architectures for integrated control and supervision of interconnected MIMO plants* (Dimirovski and co-authors, 1996, Stankovski and Dimirovski, 1998; Stankovski and co-authors, 1999) just discussed. The goals and the margins of controlled processes may be mapped onto formal models of inputs to the supervisory control level in terms of a family of primitives and sets of rules along with certain additional data for refinement or tuning.

4.1. MIMO, SISO or Composite MIMO - SISO Control?

The justification for full MIMO compensation is not always clear. In practice, as in the case of industrial thermal systems, is and often counter-indicated. Yet, even decentralised control is not achieved without difficulty. Firstly, the I/O variable pairing problem should be solved to discover which actuator should be used to affect a specified control variable, and this is

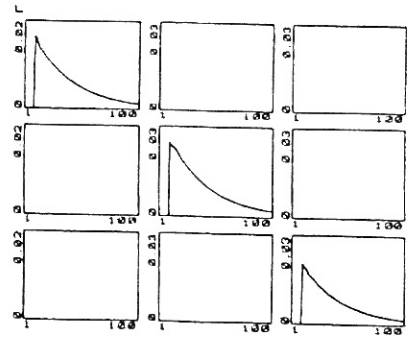

Fig. 4. The ordered characteristic I/O modes also encompassing the characteristic time-delays that are pertinent naturally to the 3zone pusher furnace RZS

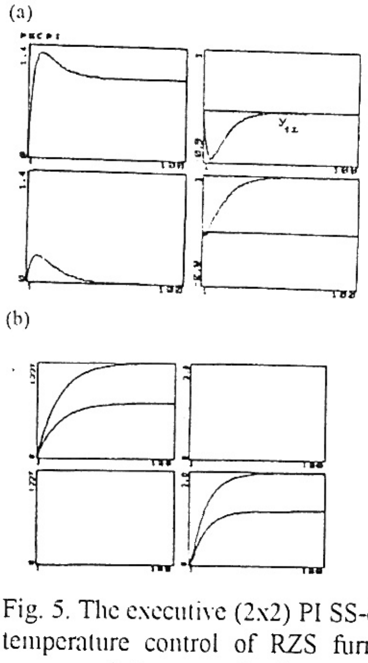

Fig. 5. The executive (2x2) PI SS-decoupling robust temperature control of RZS furnace lower-upper zones, and the respective bounds of the operational characteristic I/O modes (integrated) or uncertainty

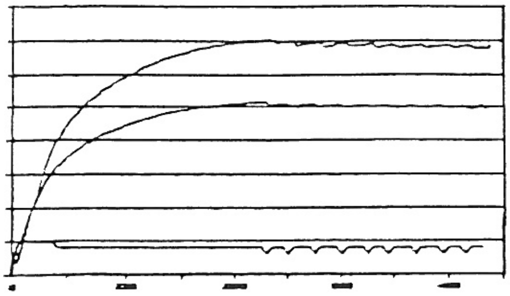

Fig. 6. The last stage (at 1000°C) performance of FPN supervisor driven co-ordinated commands and the (2x2) executive regulation to drive the upper (1250°C) and lower zone (1350°C) temperatures to the operating regime of slab/ingot heat processing

not trivial since, for instance, there are 130 possibilities for a 4x4 system. Then the *tuning problem* should be tackled by designing the individual controller blocks, but interactions limit the performance achievable and the results may lack robustness to perturbations and uncertainties (Doyle and Stein, 1988; Porter and Othman, 1990; Backx, 1993). However, it is very important to note that the system should have considerable *integrity*, i.e. remain stable if any of the controls is put on manual, or any actuator/ transducer fails in an open state. The issue on integrity gave rise to the conclusion that full dynamic decoupling may not be useful practically, though the steady-sate decoupling turn out to be rather useful in resolving MIMO control problem of complex industrial process.

Conventional controls are generally implemented as SISO feedback loops, ether analogue or digital, (Gough and co-authors, 1994, 1996) even though there may be significant interactions between the loops. This implementation arises from the practical need for simplicity of implementation, and a widespread view amongst practising engineers that full MIMO, or a combination of partial MIMO and a couple of SISO as in our case of large, high-power furnace) control systems are difficult to understand, design and implement. Usually, it is termed decentralised control.

The design of furnace process control systems for interconnected zone, high-power large furnaces with a sub-system of safety-critical control loops, belongs to this class of systems and control engineering design problems, and present authors have more than two decades of experience. Being a class of non-minimum phase systems with delays, the actual limitations on control performance is due to system dynamics and appealing for investigation: time-delays and right-half-plane zeros give the upper bounds to achievable bandwidth of the closed-loop system (Astroem, 1997).

In here, only some results (see Figures 2 to 6) on the case-study of gas/oil-fired pusher furnace RZS (Fig.1) for thermal treatment of steel ingots/slabs at Skopje Steelworks (three zones, total 25x12x8 m, 28MW) are presented. Families of steady-state (SS) and dynamic process models were identified at operating points 700-900 °C / 1000-1150 °C / 1200-1400 °C. It should be noted, simplified low-order models were utilised for actually designing furnace controls (Figs. 3) leading to implementation of a composite schemes of one (2x2) or (3x3) control and one (1x1) controls, respectively, which in turn enhanced real-time process control. Interested reader may find full detail in cited authors' references, and references therein.

4.2. The Premises of Identified Modes

In a real-world N_{inp} x N_{out} furnace and within given operating conditions and plant environment, pragmatically, design starts with identification of a family of steady-state, non-linear, convex, input/output equations representing "*energy supply m_j / controlled temperatures T_i*" (see Figs. 2, 3, 6). That is:

$$T_i = f_i\,(m_j,\ m_k = \text{const},\ k \neq j) = y_i,\ i = N_{out},$$

$$\text{at}\ \ t_{SS} = \{t_{ss}\}_{OpPoint}\,, \tag{4.1}$$

and pseudo-impulse responses or weighting patterns

$$[G(t)] = [g_{ij}(t)]_{Nout\ x\ Ninp\ x\ Nt},\ t_0 < t < t_{SS} < t_{oo}\,, \tag{4.2}$$

using admissible inputs with regard to respective magnitude ranges, typically around the three operating points of low, medium, and normal or maximum loads.

In principle, any identification method and signal processing may be used. For well-posed processes having finite steady states, e.g. industrial furnaces, pragmatic reasons stimulate most often the well-known methods of statistic regression analysis – for the family of static models termed control I/O characteristics, and step-response or maximum-length PRBS-response; at least three families of dynamic models are used according to the loads. After appropriate filtering, all these models are easily mapped into time sequences truncated at time N_t and k-time sequence matrices, $t_0 < k < k_{Nt}$, with an appropriate sampling period T_s (kTSM), that is, a Toeplitz operator derived from the sequence of MxM (N_{inp}xN_{out}) Markov matrices G(k) of plant pseudo-impulse responses or weighting patterns (Iohvidov, 1982; Backx, 1987). These models may be turned into matrices of approximate channel-transfer functions of second or first order with or without time-delay (e.g. Küpfmüller-Strejc and/or Ziegler-Nichols types). Equivalent discrete-time state-equation realisations via dyadic forms (Owens, 1979) are readily derived thereafter. Thus identified models in all forms relevant to the time domain approach are available:

$$y(k) = [g_{ij}(l)]_{Nout\ x\ Ninp\ x\ Nt} * \mathbf{m}(k),\ \ t_0 < l \leq k \leq k_{Nt}\ \ \text{with}$$

$$[g_{ij}(l)]_{Nout\ x\ Ninp\ x\ Nt} =\sim [g_{ij}(l)]_{Nout\ x\ Ninp\ x\ Ntoo}\ \ \textit{if and only iff}$$

$$\lim_{N \dashrightarrow Nt} \{[g_{ij}(l)]_{Nout}\, x_{Ninp}\}^{Nt} = \lim_{N \dashrightarrow Nt} \{[g_{ij}(l)]_{Nout}\, x_{Ninp}\}^{Nt+1}; \tag{4.3}$$

$$\mathbf{y}(q^{-1}) = [G(q^{-1})]_{N_{out} \times N_{inp}}\, \mathbf{m}(q^{-1})\ ; \tag{4.4}$$

$$\mathbf{x}(k) = [A(T_s)]_n \mathbf{x}(k-1) + [B(T_s)]_{N_{inp}} \mathbf{m}(k-1),$$

$$\mathbf{y}(k) = [C]_{N_{out}} \mathbf{x}(k). \tag{4.5}$$

In real-world processes, information propagation takes place along with flow and processing of energy and matter. Moreover, their behaviour depend essentially on the magnitude of manipulated variables, and hence the concept of energy balance within control loops is indispensable (Dimirovski and co-workers, 1977, 1979; Hanus and Kineart, 1989). However, from the energy balance point of view, the power contained in a kTSM operator of G can be well-defined (Dimirovski and co-authors, 1993)

$$P=\sum_{i=1}^{M}\left(\sum_{j=1}^{M}\lambda_j^2(k)\right)C_i=\sum_{i=1}^{M}\pi_i C_i\,,\quad \sum_1^M C_i = I\,, \tag{4.6}$$

$$V^{-1}\Lambda V = W\Lambda V = G = [g_{ij}(k)]_{M\times M\times N},\ C_i = w_i v_i^T\,, \tag{4.7}$$

in terms of signal power distribution by the *constituent matrices* C_i *(CMs)* of the characteristic I/O process modes $\Lambda = \left[\lambda_i(k)\right]_{M\times M\times N}$, $M=N_{out}=N_{inp}$, $N=N_t$. Then, an efficient algorithm for proper I/O pairing for MIMO systems on the grounds of recorded k-time sequences has been derived in there. Hence, the regulatory control system designed does comply with the natural I/O modes, which give rise to digital control algorithms with the strongest impact and most efficient actions; however, note that this is resolved in non-realan off-line activity. The issue of learning identification or predicting the range of time-delays and the upper/lower bounds of I/O modes is an iterative on-line activity. Within two-level overall control system, in turn, the reward is the gained feasibility to change the operating executive regulation controls accordingly in extended real-time (Stankovski and Dimirovski, 1998).

6. CONCLUSIONS

An applications oriented, control systems engineering approach via learning iterative identification and design for a class of well-posed industrial thermal systems having well-defined set of steady-state operating regimes has been presented. For well-posed furnaces, our approach is consistent with most of the theoretical results in systems and control sciences as well as in computer process control that are employ the steady-state decoupling and partial dynamic decoupling.

The supervisory control level, based on fuzzy-Petri-net model and data-driven execution algorithms, generates command set-ups for the distributed executive controls on the grounds of a fuzzy-rule knowledge-base. This FKB defines typical operating regimes in terms of temperature-time trajectories and typical operational loads. On the executive control level, it makes direct use of the time-domain I/O characteristic modes in terms of k-time sequence matrices. Digital regulation controls implemented - (2x2) or (3x3) PI SS-decouping plus (1x1) PI control laws - are fairly simple, well understood and easily maintained.

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