VISION-BASED FEEDBACK CONTROL STRATEGY FOR AN INDUSTRIAL BAND OVEN

Corrado Guarino Lo Bianco, Massimo Romano, and Aurelio Piazzi

University of Parma - Dip. di Ingegneria dell'Informazione,
Parco Area delle Scienze, 181/A - 43100 Parma - Italy,
Tel. + 39 0521 905752, Fax. + 39 0521 905723,
E-mail: {guarino, romano, piazzi}@ce.unipr.it

Keywords: vision inspection, uncertain model, band oven, adaptive control, fuzzy control.

Abstract

This paper describes a control application based on the vision inspection of an industrial process: a continuous band oven used to bake biscuits. The purpose of the paper is to propose a control strategy able to improve the quality of the baked products and the efficiency of the baking process. The controller feedback is provided by a vision inspection system which evaluates the cookies baking condition on the basis of the biscuits color.

1 Introduction.

Vision inspection systems are becoming very common in industrial applications. Several reasons justify the diffusion of such a technology. In many practical cases, the most relevant characteristics of industrially produced items concern their shape and color. For example, high quality ceramic tiles must be inspected in order to detect and discard damaged or out of standard pieces. In other applications it is important to detect defects in the raw materials (paper and glass production). These inspection activities have been historically managed by means of the human vision. The purpose of an automatic vision inspection systems is to substitute the human operator in this annoying activity and to improve the product quality by eliminating the subjectivity which is intrinsic in case of human inspection.

To this aim, the European Commission has recently activated a cluster of projects named "EUropean Take-up of essential Information Society Technologies-Integrated Machine Vision" (EUTIST-IMV) devoted to the introduction of the machine vision in the industrial automation (see also the web site `http://www.spt.fi/eutist/`). This paper will describe one of these projects named "quality COntrOl of baKIng status of ovEn productS" (COOKIES). The project name well synthesizes the application. The objective is to implement an autonomous feedback controller to supervise the baking process in an industrial band oven used to cook biscuits. The main information used by the closed loop controller is the baking condition of the biscuits, which is evaluated with the help of a vision inspection system.

The test quality of baked products made by means of vision inspection is described in several works of the literature. For example, in [4] the luminance signal detected by a vision system is analyzed with a fuzzy algorithm to evaluate the baking condition of industrially cooked biscuits. The same problem is considered also in [7], but the product quality is evaluated with the help of an artificial neural network. In the same paper, the importance of considering color images is evidenced. The target of the COOKIES project is even more ambitious since the vision system is used to control the baking process by acting on one of the oven burners. The final target is to improve the product quality and reduce the food scraps.

Three units are collaborating to develop the COOKIES project. The ATE unit is the industrial partner responsible for the vision acquisition system, while the University of Parma is developing the feedback control system. The project end user is the Colussi S.p.A. of Petrignano di Assisi: the supervisory feedback system will be used to control one of its continuous band ovens.

This paper describes the adaptive control strategy proposed to handle the baking process. It is based on a hybrid fuzzy supervisor. Fuzzy controllers are often used for the regulation of heating processes [3, 6, 1]. The purpose of the fuzzy supervisor used in this work is to select the most appropriate oven control strategy.

In § 2 the plant is described and the structure of the controller is briefly summarized. The vision inspection system is described in § 3, while § 4 reports with details the adopted control strategy. The result of a control simulation is shown and commented in § 5. Final conclusions are drawn in § 6.

2 The band oven and the overall control scheme.

A band oven is made of several independent cooking stations. The product "travels" through these stations carried by a band conveyer (see Fig. 1). For each station it is possible to set the burner temperature to appropriately warm up the air flux used to cook the biscuits. Moreover, several mechanical valves are used to correctly drive the air flux inside the cooking chambers and to regulate the air exchange with the external environment.

All these settings are normally tuned by the so called "oven manager", an experienced technician with many years of activ-

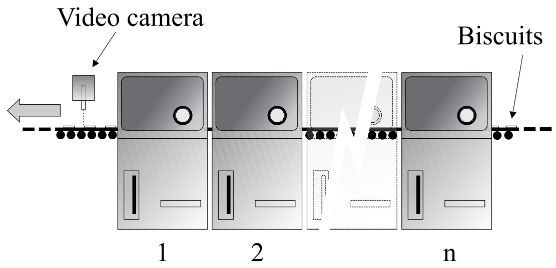

Figure 1: Schematic representation of a continuous band oven composed by n elements.

Figure 2: The Colussi band oven at the Petrignano di Assisi factory.

ity. Thus, the human factor is a relevant aspect in the management of the baking process. Every day the process surveillance is entrusted to several oven managers. Each of them acts differently on the oven, basing all the decisions on the experience. As a consequence, the same product could be baked differently in the same day, even in case of constant operating conditions. This is not the sole problem arising due to the human supervision. The baking process is very sensible to several environmental factors such as air temperature, pressure, and humidity. Theoretically, if one of these factors changes, the oven manager should modify the oven settings to keep constant the product quality. Unfortunately, the oven surveillance is not continuous, so that any drift in the environmental conditions can cause large product losses. The purpose of the vision based feedback controller proposed in this paper is to overtake all these problems and guarantee a constant product quality.

The feedback controller will act on the last section of the oven, which has the largest influence on the final biscuits color. The control scheme is shown in Fig. 3. A vision data system evaluates the status of the baking process on the basis of the biscuits color. Its output is a real number, indicated in the following with the term of "Baking Status" (BS), representing the average cooking status of the biscuits. The variable BS is used by the control system to impose a proper set-point for the burner temperature. The plant characteristics impose to use an adaptive control scheme. It is governed by a fuzzy supervisor who

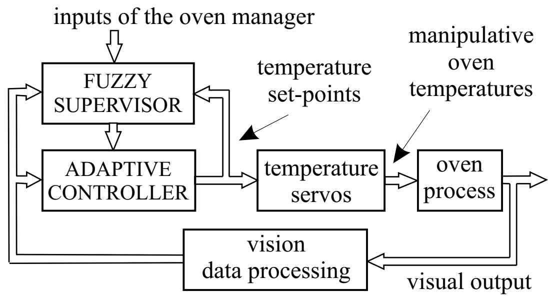

Figure 3: Control scheme for the continuous band oven.

has to select the most appropriate control strategy depending on the working conditions. The video camera used to acquire the biscuit status is located at the outlet of the oven (see Fig. 1). We conventionally pose $BS \in \mathbb{R}$: when $BS = 0$ the biscuits are considered well cooked, while $BS > 0$ and $BS < 0$ indicate overcooked and undercooked biscuits respectively. The purpose of the feedback controller is to guarantee, by regulating the burner temperature of the last section, that the baking status is always as close as possible to zero.

3 Baking status estimation via visual data processing.

The main element of the vision system is a color digital line-scanning camera equipped with a specific optics. The line-scanning camera is placed above the oven belt. Its visual range fully covers the transversal section of the conveyer, so that it can inspect simultaneously an entire row of biscuits. Biscuits are illuminated with a special light source which minimizes the influence of the external undesired lightening. The acquired data are analyzed by means of a Digital Signal Processing (DSP) board which evaluates the baking status of the biscuits. The elaboration results are downloaded to a supervisory Personal Computer by means of a fast serial link.

The vision system has been completely developed and manufactured by ATE. The use of a color camera is justified by the same reasonings reported in [7]. Due to the use of color images, it is possible to sense small changes in the baking status. This is a relevant feature because such information is used for the closed loop control.

The vision system can inspect all biscuits on the belt, so that it can detect any possible defect of each biscuit: nonuniform baking, wrong shape, scraps (see e.g. fig. 4). This information will be used to drive an automatic discard system. The baking status signal BS is obtained as an averaged measure. The reason of this averaging operation is that biscuits laterally placed on the conveyer are normally more baked than biscuits placed in the middle. This is typical for large gas-driven baking lines and the averaging operation solves the problem. Moreover, the baking status is also averaged along the longitudinal section of the oven to filter the vision measurement noise.

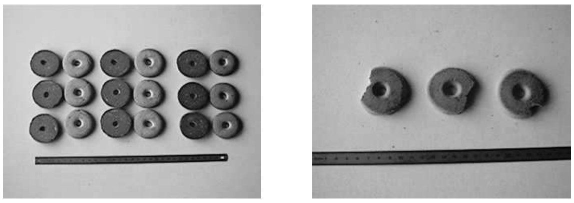

Figure 4: a) Cookies with different baking statuses; b) Damaged cookies.

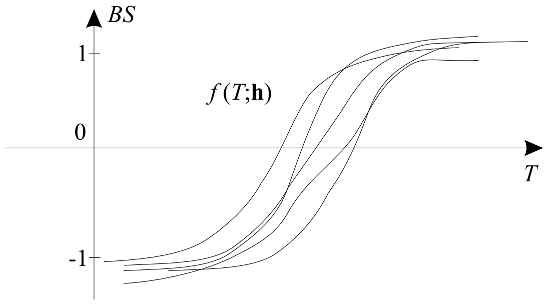

Figure 5: The static baking status as a function of the burner temperature.

4 The control strategy.

The biscuit baking is a nonlinear, dynamic process influenced by many factors: some of them depend on human actions (valves positions, band velocity) while others depend on environmental conditions (external temperature, pressure, humidity). These factors can be quantified by means of real numbers collected into a vector $\mathbf{h} \in \mathcal{H} := [h_1^-, h_1^+] \times \cdots \times [h_p^-, h_p^+] \subset \mathbb{R}^p$, where p indicates the number factors influencing the process. The system behavior is uncertain since it depends on $\mathbf{h}$ and its identification is difficult because of two reasons. First, the number of uncertainties is very large and many of them are difficult to be quantified. Secondly, to collect a sufficiently large number of experimental data of various operating conditions, it should be necessary to burn-off or undercook large amounts of biscuits. As a consequence, due to the scarce system knowledge, it is difficult to design a robust dynamic controller. The controller proposed in this paper aims to solve this problem by mimicking the human behavior. The biscuit baking is a stable process so that, given a burner set-point T, the baking status BS always converges to a finite value which depends also on the environmental factors $\mathbf{h}$. Thus, the condition $BS = 0$ can be gained by passing through a sequence of steady states. The control approach can be summarized as follows. Consider the system in steady state and with $BS \neq 0$. If both these conditions hold, the burner set-point is changed using one of the rules proposed in the following. Then, the controller monitors BS to detect the transient end: new changes of the burner temperature are allowed only when a new steady state is (almost) reached.

It is possible to represent the static behavior of BS by means of the following function

$$f : \mathcal{T} \times \mathcal{H} \to \mathbb{R}$$

$$(T; \mathbf{h}) \to f(T; \mathbf{h})$$

where $\mathcal{T} := [T^-, T^+] \subset \mathbb{R}$ is the range of admissible temperatures of the last oven section. The following characteristics of the baking function $f(T; \mathbf{h})$ can be assumed owing to simple physical reasonings.

Assumption 1 *The baking function $f(T; \mathbf{h})$ is continuous with its first derivative, i.e. $f \in C^1(\mathcal{T} \times \mathcal{H})$. Moreover, for any assigned $\mathbf{h} \in \mathcal{H}$, it is monotonically increasing with respect to T*

$$\frac{\partial f}{\partial T} > 0 \qquad \forall T \in \mathcal{T} . \tag{1}$$

A typical baking function $f(T; \mathbf{h})$ is shown in Fig. 5 by means of a family of nonlinear functions depending on $\mathbf{h}$.

The function $f(T; \mathbf{h})$ cannot be identified for the same reasons that do not allow the identification of the oven dynamic model: it should be necessary to produce a large number of badly cooked biscuits and this is unacceptable for economic reasons. Thus, the oven controller must robustly converge to $BS = 0$ independently from the knowledge of $f(T; \mathbf{h})$.

The optimal burner set-point is, theoretically, the solution of the equation $f(T; \mathbf{h}) = 0$ evaluated for any value of $\mathbf{h} \in \mathcal{H}$ and, as a consequence, it depends on the parameters $\mathbf{h}$. For this reason it will be indicated by $T^*(\mathbf{h})$. The optimal value $T^*(\mathbf{h})$ is computed by means of a recursive algorithm which uses the following two different strategies to approach the condition $BS = 0$.

Strategy 1 - Single point approach.

Given an initial burner temperature T_i and the corresponding steady-state baking status BS_i, the subsequent set-point T_{i+1} is evaluated by means of the following equation

$$T_{i+1} = T_i - \frac{BS_i}{\widetilde{K}} . \tag{2}$$

where $\widetilde{K}$ is obtained from the slope of the baking function in the neighborhood of the points where $BS = 0$. More precisely, $\widetilde{K}$ is evaluated during the normal baking operation by averaging the slopes corresponding to several values of $\mathbf{h}$. An example of the approaching strategy is shown in Fig. 6.

Strategy 2 - Two points approach.

The last two burner set-points (T_i, T_{i-1}) and the corresponding measured baking statuses (BS_i, BS_{i-1}) are required to evaluate the subsequent burner set-point T_{i+1} according to the equation

$$T_{i+1} = T_i - \frac{T_{i-1} - T_i}{BS_{i-1} - BS_i} BS_i . \tag{3}$$

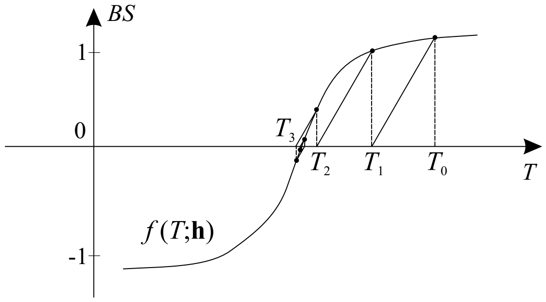

Figure 6: The optimal burner temperature is approached with Strategy 1.

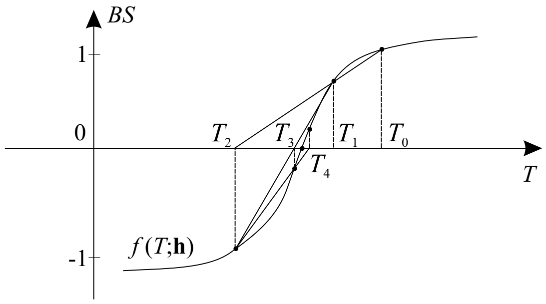

Figure 7: The optimal burner temperature is approached with Strategy 2.

The convergence steps resulting from the use of Strategy 2 are shown in Fig. 7.

There are several reasons to introduce two different searching strategies for the optimal burner temperature T^*. The first strategy robustly approaches the optimal set-point value (it will be demonstrated in the following that an appropriate selection of $\widetilde{K}$ guarantees, with certainty, the convergence to T^*) but the convergence rate could be slow. The second strategy speeds up the algorithm convergence but has several drawbacks. For example, if T_i and T_{i-1} are too far from T^* the algorithm could diverge. Moreover, equation (3) cannot be used if $T_i = T_{i-1}$ (this happens, for example, after the algorithm has converged to T^*) or when a single point is available (this happens the first time the searching algorithm is used).

At each iteration the fuzzy supervisor analyzes the set-point candidates proposed by the two strategies. The actual burner set-point is obtained by weighting the two candidates. Depending on the working conditions, the slow but safe Strategy 1 can or cannot be preferred to the fast but risky Strategy 2.

The robustness of the first strategy is proved in the following by verifying the existence of a value $\widetilde{K}(\mathbf{h})$ which guarantees with certainty the convergence toward the optimal burner temperature $T^*(\mathbf{h})$. Some preliminary hypotheses have to be assumed. The baking function $f(T;\mathbf{h})$ is affected by $\mathbf{h}$, which is a vector of slowly varying parameters. It will be supposed that $\mathbf{h}$ does not change until the algorithm has converged to $T^*(\mathbf{h})$. Moreover, it will be assumed that a solution $T^*(\mathbf{h})$ such that $f(T^*(\mathbf{h});\mathbf{h}) = 0$ exists for any $\mathbf{h} \in \mathcal{H}$. This is not an obvious condition because if the first $n-1$ ovens are not correctly working, it can happen that $f(T;\mathbf{h}) > 0$ or $f(T;\mathbf{h}) < 0$ for all $T \in \mathcal{T}$. Finally, the baking function $f(T;\mathbf{h})$ has to satisfy the Assumption 1. For this reason it is possible to assert that the partial derivative of $f(T;\mathbf{h})$ with respect to T is bounded over the compact interval $\mathcal{T}$. Thus, for any $\mathbf{h} \in \mathcal{H}$, it is possible to define

$$K(\mathbf{h}) := \max_{T\in\mathcal{T}} \left\{ \frac{\partial f}{\partial T} \right\} > 0 \; . \tag{4}$$

The strict monotonicity of $f(T;\mathbf{h})$ with respect to T permits also asserting the singleness of the solution $T^*(\mathbf{h})$.

Property 1 *Let us consider a baking function $f(T;\mathbf{h})$ satisfying Assumption 1, where $\mathbf{h}$ is a vector of constant parameters affecting the plant behavior. Moreover, assume that the equation $f(T^*(\mathbf{h});\mathbf{h}) = 0$ admits a single solution $T^*(\mathbf{h})$ for any $\mathbf{h} \in \mathcal{H}$ and choose $\widetilde{K} := \max_{\mathbf{h}\in\mathcal{H}} K(\mathbf{h})$. Then, Strategy 1 converges with certainty to $T^*(\mathbf{h})$ for any given $\mathbf{h} \in \mathcal{H}$.*

Proof - The vector $\mathbf{h}$ is supposed to be constant. The property proof is valid independently from its value so that, in the following, $\mathbf{h}$ will be omitted. Select a starting temperature $T_i < T^*$: it will be demonstrated that for any $T_i < T^*$ the Strategy 1 converges from the left to the optimal temperature T^*. Similar reasonings permit asserting that an approach from the right is obtained for any starting point $T_i > T^*$.

The updating equation (2) can be rewritten using the baking function

$$T_{i+1} = T_i - \frac{f(T_i)}{\widetilde{K}} \; . \tag{5}$$

According to Assumption 1, the baking function is monotonically increasing and, moreover, $f(T_i) = 0$ if and only if $T_i = T^*$. As a consequence, for any $T_i < T^*$ it is possible to write $f(T_i) < 0$. Taking into account that $\widetilde{K} > 0$, it is possible to conclude that for any $T_i < T^*$ the updating equation (5) generates an updating temperature T_{i+1} such that

$$T_{i+1} > T_i \; . \tag{6}$$

By integrating $\partial f/\partial T$ it is possible to write

$$\begin{aligned} f(T_{i+1}) &= f(T_i) + \int_{T_i}^{T_{i+1}} \frac{\partial f}{\partial T}(\tau)d\tau \\ &\leq f(T_i) + \int_{T_i}^{T_{i+1}} \widetilde{K} d\tau \\ &= f(T_i) + \widetilde{K}(T_{i+1} - T_i) \; . \end{aligned}$$

Thus, taking into account (5), the following inequality holds

$$f(T_{i+1}) \leq f(T_i) + \widetilde{K}(T_{i+1} - T_i) = 0 \; . \tag{7}$$

By combining this inequality with (6) it is possible to conclude that Strategy 1 generates a succession of temperature set-points

T_i monotonically increasing but always located on the left of T^*. A well known result of the analysis makes it possible to assert that such succession must converge to a finite value T_c. Thus, the succession satisfies the Cauchy condition

$$\lim_{i\to\infty} |T_{i+1} - T_i| = 0 \quad (8)$$

Taking again into account (5), it is possible to write

$$\lim_{i\to\infty} |T_{i+1} - T_i| = \lim_{i\to\infty} \frac{f(T_i)}{\widetilde{K}} = \frac{f(T_c)}{\widetilde{K}} \; . \quad (9)$$

By comparing (8) and (9), it is possible to conclude that $f(T_c) = 0$ and, evidently, $T_c = T^*$. □

Remark 1 *In the demonstration of Property 1, the parameter vector* $\mathbf{h}$ *is supposed to be constant. This is not a limiting condition since part of the parameters in* $\mathbf{h}$ *change slowly (meteorological conditions) while others change suddenly but rarely (valves positions): in both cases the control algorithm has enough time to gain the optimal temperature* T^**.*

Remark 2 *By selecting* $\widetilde{K}$ *according to Property 1 and using Strategy 1, the optimal temperature* T^* *is gained with certainty with the drawback of a slow convergence rate. For this reason, in the actual application* $\widetilde{K}$ *is obtained by averaging values of* $\frac{\partial f}{\partial T}(T^*)$ *collected during previous runs of the algorithm. The choice is sufficiently safe and, in any case, non converging behaviors can be easily corrected by increasing the current value of* $\widetilde{K}$*.*

The overall control algorithm is based on the combination of the two searching strategies and can be summarized as follows

1. $\widetilde{T}^*$-init($\widetilde{T}^*$); $T_{old} \leftarrow \widetilde{T}^*$;
2. Equilibrium procedure (BS_{old});
3. Strategy 1 procedure ($\widetilde{T}^*$); $T_{new} \leftarrow \widetilde{T}^*$;
4. Equilibrium procedure (BS_{new});
5. Repeat
6. $\quad$ $\widetilde{T}^*$-update($\widetilde{T}^*$);
7. $\quad$ $T_{old} \leftarrow T_{new};\ BS_{old} \leftarrow BS_{new}$;
8. $\quad$ Equilibrium procedure (BS_{new});
9. $\quad$ $T_{new} \leftarrow \widetilde{T}^*$;
10. Until Stop

The procedure $\widetilde{T}^*$-init evaluates the initial set-point of the burner temperature $\widetilde{T}^*$ on the basis of $\mathbf{h}$. It uses a function $\widetilde{T}^*(\mathbf{h})$ estimated during previous runs of the controller. The equilibrium procedures are used each time the oven set-point is changed: they are used to stop the algorithm until the end of the thermal transients. Finally, the $\widetilde{T}^*$-update procedure evaluates the new $\widetilde{T}^*$ by properly combining the set-point proposal of the two strategies.

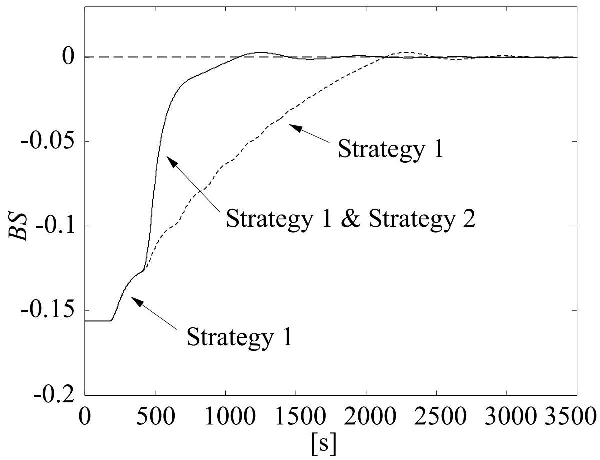

Figure 8: Comparison between transient times: the simultaneous use of both Strategy 1 and 2 (continuous line) permits shorter transients than those obtained using the sole Strategy 1 (dashed line).

5 Simulation results.

The control strategy proposed in the previous section has been simulated by means of Simulink. The dynamic baking model used for the simulations [2] takes into account many of the factors that normally affect the cooking process. For example, the oven thermal transients are accurately modelled as well as several nonlinear effects that are typical of the baking process [5]. The model is time variant. Figure 8 shows a typical transient and evidences the benefits deriving from the two strategies approach proposed. In a first simulation (dashed line) the condition $BS = 0$ is gained using exclusively the Strategy 1, while the combined approach proposed in the previous section is used for the second simulation (continuous line). By comparing the two responses, it is possible to observe that, at the beginning, the two transients coincide because both controllers use Strategy 1. Then, the fuzzy supervisored controller starts using also Strategy 2 and the status $BS = 0$ is reached faster.

6 Conclusions.

A strategy for the control of a continuous band oven has been proposed in this paper. A feedback action, based on the biscuits vision inspection, has been used to evaluate the most appropriate burner temperature. The simulation result reported in § 5 shows that the proposed controller is able to evaluate the optimal burner temperature with a limited number of attempts. This is a very relevant feature which makes it possible to reduce the amount of product scraps. Moreover, the controller can robustly handle the typical uncertainties of the baking processes.

Acknowledgments

This work was supported by the "EUropean Take-up of essential Information Society Technologies-Integrated Machine Vision" (EUTIST-IMV).

The authors wish to acknowledge Renzo Santi, Federico Ghirelli, Roberto Martini and Daniela Oliviero (Colussi S.p.A.) and Guy Lemström (ATE) for their precious collaboration. A special thank to Otello Mazzoni ("The lord of the ovens"- Colussi S.p.A.) for his witty descriptions of the oven behaviors.

References

[1] Gao, Z., Trautzsch, T. and Dawson, J.: 2002, A stable self-tuning fuzzy logic control system for industrial temperature regulation, *IEEE Transactions on Industry Applications* **38**(2), 414–424.

[2] Guarino Lo Bianco, C., Romano, M. and Piazzi, A.: 2002, A nonlinear dynamic model for the baking process in continuos band ovens, *Technical Report TSC-01/02*, University of Parma.

[3] Jikai, Y., Hongping, Y., Hongtao, S. and Yuanbin, H.: 1997, Fuzzy control technique based on genetic algorithms optimizing and its application, *IEEE International Conference on Intelligent Processing Systems, ICIPS97*, Vol. 1, Beijing, China, pp. 329–333.

[4] Perrot, N., Bonazzi, C., Trystram, G. and Guely, F.: 1999, Estimation of the food product quality using fuzzy sets, *18th International Conference of the North American Fuzzy Information Processing Society, NAFIPS*, New York, NY, pp. 487–491.

[5] Trysram, G., Fahoul, D., Duquenoy, A. and Allache, M.: 1993, Dynamic modelling and simulation of the biscuit baking oven process, *Computers Chemical Engineering* **17**(supp), 203–208.

[6] Xinxin, Y., Lei, Y., Kezhong, H., Shengle, H., Muhe, G. and Bo, Z.: 1996, A double-level fuzzy controller with an intelligently adjusting strategy of quantization and scale factors, *IEEE International Conference on Systems, Man, and Cybernetics*, Vol. 1, Beijing, China, pp. 280–285.

[7] Yeh, J., Hamey, L., Westcott, T. and Sung, S.: 1995, Colour bake inspection system using hybrid artificial neural networks, *Proceedings of the IEEE International Conference on Neural Networks*, Vol. 1, Perth, Western Australia, pp. 37–42.