Application of self-tuning polynomial controller and comparison with standard controller

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***Abstract*—** The article deals an implementation of a numerical adaptive self-tuning controller for a usage in a drying machine in a production of small amount printed circuits boards. The controller is design to use in a 8-bit microcontroller from DZ family produced by Freescale Semiconductor providing main functions – temperature measuring and control, communication with PC. That microcontroller is a main part of the dryer, but other parts (triacs and drivers) are indispensable.

A dryer dynamic system is identified during a control process by a recursive least-square method. The controlling part is calculated on the basis of a dead beat control method. Of course, it is verified on a real device with surroundings which independently change temperature and air flow and it is compared with a non-adaptive controller.

***Keywords*—**Discrete controller, drying machine, 8-bit microcontroller, recursive identification, dead beat control method.

I. Introduction

Nowadays, a fast production of printed circuits boards is needed – especially in processes of designing and developing electronic circuits, controllers, RF parts. These devices are made in a wide range from simple circuits for specific purpose in a small amount production to universal circuits with configurable functions. Printed circuit boards (PCB) for those circuits can be produced with a different quality (usually classes III-IX) an amount and types. The simplest type of boards is made as a one side board without any conformal protection layer (non-soldering mask, tin plating). Demands on board's quality rise together with development electronics, primarily number of layers (double-sided boards, four-layers boards) and surface treatment (non-soldering layers, HAL, golden plating, service printing).

Commonly available non-soldering mask has to resist to high temperatures during soldering (manual, reflow or wave soldering), chemical cleaning and mechanical damage. High amount of SMD devices cannot be proper soldered without mask, for example BGA and QFN packages). Due to these reasons, parameters of applying mask and specially drying temperature have to be exactly kept during the PCB manufacturing. A tolerance is prescribed by producer of the mask; it usually achieves 10°C depending on drying method (horizontally, vertically, single board or high amount of boards), air flow and ventilation [9]. If the tolerance is exceeded, the mask lost an adhesion to the board or the mask holds on the board to strong on places where component pads are designed. It depreciates the board or the board is overall unusable. As can be seen on Fig. 1, a PCB sample is losing the mask, because the drying temperature was out of tolerances and didn't achieve the set temperature.

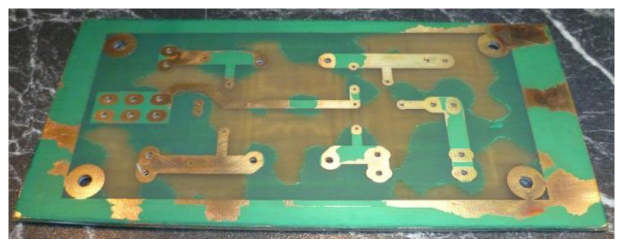

Fig.1 Non-soldering missing mask on the PCB

This work presents a design of the polynomial adaptive controller for a temperature control in the process of the PCB manufacturing. The controller is universally designed to using with large types of dryers independent on type, dimensions or power. Implementation is established on 8-bit Freescale microcontroller (HCS08 type). Controller calculation and hardware implementation are solved in next chapters. It is followed by verification of controller on a real device (a small dryer with usable dimensions for PCB up to 200x300mm).

II. Recursive Identification

The recursive identification – the least-square method [2], [4], [5], [11] is used to unsure a high stability of the controlled temperature during the changing of surroundings conditions. This method need no huge space memory in the microcontroller and complicated calculations, because two last steps of controller output value and temperature are sufficient to provide dynamic system identification.

It can be deduced from dryer knowledge, that system can be described by the second-order discrete function

$$G(z)=\frac{b_1 z^{-1}+b_2 z^{-2}}{1+a_1 z^{-1}+a_2 z^{-2}}. \qquad (1)$$

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An implicit least-square identification method gets parameters by minimizing of summary squared errors. The equation (2) is considered

$$y(k)=\sum_{i=1}^{r}a_i f_i(k)+e(k), \qquad (2)$$

where $e(k)$ is an error, and a_i are unknown parameters. Next, for the error can be written

$$e(k)=y(k)-y_m(k)=y(k)-\sum_{i=1}^{r}a_i f_i(k), \qquad (3)$$

which is a difference of measured values $y(k)$ and modeled values $y_m(k)$ calculated by a regress calculation. The least square criterion can be written as (4)

$$J=\sum_{k=1}^{N}e^2(k)=\sum_{k=1}^{N}\left[y(k)-\sum_{i=1}^{r}a_i f_i(k)\right]^2. \qquad (4)$$

The criterion reaches a zero value if partial derivations by each parameter are equal to zero. A system of equations, which was got by a successive substitution of measured values into (2), has next form:

$$\begin{aligned} y(1)&=a_1 f_1+a_2 f_2(1)+\cdots+a_r f_r(1)+e(1)\\ y(2)&=a_1 f_1+a_2 f_2(2)+\cdots+a_r f_r(2)+e(2)\\ &\vdots\\ y(N)&=a_1 f_1+a_2 f_2(N)+\cdots+a_r f_r(N)+e(N) \end{aligned}. \qquad (5)$$

If the next vectors are defined as

$$\begin{aligned} \mathbf{y}^T&=[y(1)\quad y(2)\quad \cdots\quad y(N)]\\ \mathbf{\Theta}^T&=[a_1\quad a_2\quad \cdots\quad a_r]\\ \mathbf{e}^T&=[e(1)\quad e(2)\quad \cdots\quad e(N)] \end{aligned} \qquad (6)$$

and matrix

$$\mathbf{F}=\begin{bmatrix} f_1(1) & f_2(1) & \dots & f_r(1)\\ f_1(2) & f_2(2) & \dots & f_r(2)\\ \vdots & \vdots & \vdots & \vdots\\ f_1(N) & f_2(N) & \dots & f_r(N) \end{bmatrix} \qquad (7)$$

with dimension (N,r), the equation system can be written by equation

$$\mathbf{y}=\mathbf{F\Theta}+\mathbf{e}. \qquad (8)$$

Due to the (8), the error can be written as

$$\mathbf{e}=\mathbf{y}-\mathbf{F\Theta}. \qquad (9)$$

It can be seen that the square criterion is a scalar, which can be expressed by equation

$$\mathbf{J}=\mathbf{e}^T\mathbf{e}=(\mathbf{y}-\mathbf{F\Theta})^T(\mathbf{y}-\mathbf{F\Theta})\rightarrow \min. \qquad (10)$$

The criterion minimum can be achieved by derivation

$$\left.\frac{\partial J}{\partial \mathbf{\Theta}}\right|_{\mathbf{\Theta}=\hat{\mathbf{\Theta}}}=0. \qquad (11)$$

Next equations are achieved after derivation:

$$\begin{aligned} \frac{\partial J}{\partial \hat{\mathbf{\Theta}}}&=\frac{\partial\left(y-\mathbf{F}\hat{\mathbf{\Theta}}\right)^T}{\partial \hat{\mathbf{\Theta}}}\left(y-\mathbf{F}\hat{\mathbf{\Theta}}\right)+\frac{\partial\left(y-\mathbf{F}\hat{\mathbf{\Theta}}\right)^T}{\partial \hat{\mathbf{\Theta}}}\left(y-\mathbf{F}\hat{\mathbf{\Theta}}\right)=\\ &=-\mathbf{F}^T\left(y-\mathbf{F}\hat{\mathbf{\Theta}}\right)-\mathbf{F}^T\left(y-\mathbf{F}\hat{\mathbf{\Theta}}\right)\\ &=-2\mathbf{F}^T\left(y-\mathbf{F}\hat{\mathbf{\Theta}}\right)=0 \end{aligned}. \qquad (12)$$

If equation (12) is solved, we get

$$\mathbf{F}^T\left(y-\mathbf{F}\hat{\mathbf{\Theta}}\right)=0 \qquad (13)$$

and we can modify (13) to

$$\hat{\mathbf{\Theta}}=\left(\mathbf{F}^T\mathbf{F}\right)^{-1}\mathbf{F}^T\mathbf{y}. \qquad (14)$$

It can be simplified to

$$\hat{\mathbf{\Theta}}=\mathbf{F}^{-1}\mathbf{y}, \qquad (15)$$

but it can be applied only for square matrix **F,** therefore $r=N$. Mean value $\hat{\mathbf{\Theta}}$ can be calculated by

$$\begin{aligned} \hat{\mathbf{\Theta}}&=\left(\mathbf{F}^T\mathbf{F}\right)^{-1}\mathbf{F}^T\mathbf{y}=\left(\mathbf{F}^T\mathbf{F}\right)^{-1}\mathbf{F}^T(\mathbf{F\Theta}+\mathbf{e})=\\ &=\left(\mathbf{F}^T\mathbf{F}\right)^{-1}\mathbf{F}^T\mathbf{F\Theta}+\left(\mathbf{F}^T\mathbf{F}\right)^{-1}\mathbf{Fe}=\Theta+\left(\mathbf{F}^T\mathbf{F}\right)^{-1}\mathbf{F}^T\mathbf{e} \end{aligned} \qquad (16)$$

Next equation is applied for mean value of parameters estimation

$$E\left[\hat{\mathbf{\Theta}}\right]=\hat{\mathbf{\Theta}}+E\left[\left(\mathbf{F}^T\mathbf{F}\right)^{-1}\mathbf{F}^T\mathbf{e}\right] \qquad (17)$$

Estimation is impartial if $E\left[\hat{\mathbf{\Theta}}\right]=0$. Therefore, it must be applied in equation (17) for second part

$$E\left[\left(\mathbf{F}^T\mathbf{F}\right)^{-1}\mathbf{F}^T\mathbf{e}\right]=0. \qquad (18)$$

Condition in (18) is fulfilled when parts of $\mathbf{F}$ and $\mathbf{e}$ are independent and $E(\mathbf{e})=0$. General relation (19) is applied for covariance matrix of random vector $\mathbf{z}^T=[z_1\quad z_2\quad \dots\quad z_n]$

$$\mathbf{C}[z]=E\left\{[\mathbf{z}-E(\mathbf{z})][\mathbf{z}-E(\mathbf{z})]^T\right\}. \qquad (19)$$

If error $\mathbf{e}$ is uncorrelated signal $\left(E\left[\hat{\mathbf{\Theta}}\right]=0\right)$, than covariance matrix of random part is

$$\mathbf{C}[z]=E\left\{\left[\mathbf{z}-E(\mathbf{z})\right]\left[\mathbf{z}-E(\mathbf{z})\right]^T\right\}=E\left[\mathbf{e}\mathbf{e}^T\right]=\sigma_e^2\mathbf{I}, \tag{20}$$

where σ_e^2 is error variance and $\mathbf{I}$ is unit matrix. If $E\left(\hat{\mathbf{\Theta}}\right)=\mathbf{\Theta}$, next equation can be written

$$\mathbf{C}\left(\hat{\mathbf{\Theta}}\right)=E\left[\left(\hat{\mathbf{\Theta}}-\mathbf{\Theta}\right)\left(\hat{\mathbf{\Theta}}-\mathbf{\Theta}\right)^T\right]. \tag{21}$$

If error $\mathbf{e}$ is uncorrelated, covariance matrix can calculated by

$$\mathbf{C}\left(\hat{\mathbf{\Theta}}\right)=\sigma_e^2 E\left(\mathbf{F}^T\mathbf{F}\right)^{-1}. \tag{22}$$

If matrix $\mathbf{F}$ doesn't include random parts, than $E\left[\left(\mathbf{F}^T\mathbf{F}\right)^{-1}\right]=\left(\mathbf{F}^T\mathbf{F}\right)^{-1}$ and (22) is modified to $\mathbf{C}\left(\hat{\mathbf{\Theta}}\right)=\sigma_e^2\left(\mathbf{F}^T\mathbf{F}\right)^{-1}$.
(23)

Variations of $\mathbf{e}$ are determined by calculated parameters $\hat{\mathbf{\Theta}}$. Residues are calculated from equation (8)

$$\hat{\mathbf{e}}=\mathbf{y}-\mathbf{F}\mathbf{\Theta}=\mathbf{y}-\hat{\mathbf{y}}, \tag{24}$$

where $\hat{\mathbf{y}}=\mathbf{F}\mathbf{\Theta}$ is estimation of output value – predicted output value. Residual error function

$$J_R=\hat{\mathbf{e}}^T\hat{\mathbf{e}} \tag{25}$$

can be written. If $E\left(\hat{\mathbf{\Theta}}\right)=0$, it can be applied for estimation of error variation

$$\hat{\sigma}_e^2=\frac{J_R}{N}=\frac{1}{N}\sum_{i=1}^{N}e_i^2. \tag{26}$$

For continual identification the equation (14) be rewritten for $k-1$ measurements to

$$\hat{\mathbf{\Theta}}(k-1)=\left(\mathbf{F}_{k-1}{}^T\mathbf{F}_{k-1}\right)^{-1}\mathbf{F}_{k-1}{}^T\mathbf{y}(k-1), \tag{27}$$

where

$$\mathbf{y}^T(k-1)=\left[y(1)\quad y(2)\quad \ldots\quad y(k-1)\right] \tag{28}$$

is a vector of output variables in the interval $(1,k-1)$, and

$$\hat{\mathbf{\Theta}}(k-1)=\left[\hat{\theta}_1(k-1)\quad \hat{\theta}_2(k-1)\quad \ldots\quad \hat{\theta}_r(k-1)\right] \tag{29}$$

is vector of optimal estimates of parameter values of transfer function. A matrix

$$\mathbf{F}_{k-1}=\begin{bmatrix} f_1(1) & f_2(1) & \ldots & f_r(1)\\ f_1(2) & f_2(2) & \ldots & f_r(2)\\ \vdots & \vdots & \vdots & \vdots\\ f_1(k-1) & f_2(k-1) & \ldots & f_r(k-1)\end{bmatrix} \tag{30}$$

is modified matrix $\mathbf{F}$ for $(k-1)$ measurements. If k-measurement is done and

$$\mathbf{y}(k)=\begin{bmatrix} y(k-1)\\ y(k)\end{bmatrix} \tag{31}$$

is described, the $\mathbf{F}_k$ matrix is

$$\mathbf{F}_k=\begin{bmatrix}\mathbf{F}_{k-1}\\ \mathbf{\Phi}^T(k)\end{bmatrix} \tag{32}$$

can be written, where

$$\mathbf{\Phi}^T(k)=\left[f_1(k)\quad f_2(k)\quad \ldots\quad f_r(k)\right] \tag{33}$$

The output vector can be written for k-measured variable

$$y(k)=\mathbf{\Theta}^T\mathbf{\Phi}(k)+e(k), \tag{34}$$

where $\mathbf{\Theta}^T$ is defined as

$$\mathbf{\Theta}^T=\left[\theta_1\quad \theta_2\quad \ldots\quad \theta_r\right] \tag{35}$$

A covariance matrix $\mathbf{C}(k)$ can be defined as

$$\mathbf{C}(k)=\left[\mathbf{F}_{k-1}^T\mathbf{F}_{k-1}+\mathbf{\Phi}(k)\mathbf{\Phi}^T(k)\right]^{-1}, \tag{36}$$

and it can be written as

$$\mathbf{C}(k)=\left[\mathbf{C}^{-1}(k-1)+\mathbf{\Phi}(k)\mathbf{\Phi}^T(k)\right]^{-1} \tag{37}$$

A general recursive algorithm can be written as

$$\hat{\mathbf{\Theta}}(k)=\hat{\mathbf{\Theta}}(k-1)+\mathbf{K}(k)\left[y(k)-\hat{\mathbf{\Theta}}^T(k-1)\mathbf{\Phi}(k)\right] \tag{38}$$

where $\mathbf{K}(k)$ is a time changing vector of gain and can be written as

$$\mathbf{K}(k)=\frac{\mathbf{C}(k-1)\mathbf{\Phi}(k)}{1+\mathbf{\Phi}^T(k)\mathbf{C}(k-1)\mathbf{\Phi}(k)} \tag{39}$$

The recursive equation for the covariance matrix is

$$\mathbf{C}(k)=\mathbf{C}(k-1)-\mathbf{C}(k-1)\frac{\mathbf{\Phi}(k)\mathbf{\Phi}^T(k)\mathbf{C}(k-1)}{1+\mathbf{\Phi}^T(k)\mathbf{C}(k-1)\mathbf{\Phi}(k)} \tag{40}$$

The vector of parameters $\mathbf{\Theta}^T(k)$ and vector of measured data $\mathbf{\Phi}^T(k)$ can be written for the second order transfer function as

$$\mathbf{\Theta}^T(k) = [a_1 \quad a_2 \quad b_1 \quad b_2] \tag{41}$$

$$\mathbf{\Phi}^T(k) = [-y(k-1) \quad -y(k-2) \quad u(k-1) \quad u(k-2)] \tag{42}$$

III. Discrete Controller

The dead beat controller was chosen for the dryer. This controller ensures the stability of regulated variable also among measurement periods [2-4], [10]. The closed loop can be described by equations (43) and (44):

$$Y(z^{-1}) = \frac{B(z^{-1})}{A(z^{-1})} U(z^{-1}) \tag{43}$$

$$U(z^{-1}) = \frac{R(z^{-1})}{P(z^{-1})} W(z^{-1}) - \frac{Q(z^{-1})}{P(z^{-1})} Y(z^{-1}) \tag{44}$$

where $U(z^{-1})$, $Y(z^{-1})$ and $W(z^{-1})$ are polynomials of corresponding signals. Controller output $U(z^{-1})$ and regulated signal $Y(z^{-1})$ can be written after modification of (43) and (44):

$$Y(z^{-1}) = \frac{B(z^{-1})R(z^{-1})}{A(z^{-1})P(z^{-1}) + B(z^{-1})Q(z^{-1})} W(z^{-1}) \tag{45}$$

$$U(z^{-1}) = \frac{A(z^{-1})R(z^{-1})}{A(z^{-1})P(z^{-1}) + B(z^{-1})Q(z^{-1})} W(z^{-1}) \tag{46}$$

and control error $E(z^{-1})$

$$E(z^{-1}) = \left[1 - \frac{B(z^{-1})R(z^{-1})}{A(z^{-1})P(z^{-1}) + B(z^{-1})Q(z^{-1})}\right] W(z^{-1}) \tag{47}$$

If control error is required to be zero in finite steps, the polynomial $E(z^{-1})$ has to be simple. This condition is satisfied if polynomial equation

$$A(z^{-1})P(z^{-1}) + B(z^{-1})Q(z^{-1}) = 1. \tag{48}$$

It has solution for

$$\begin{aligned} \partial P(z^{-1}) &= \partial B(z^{-1}) - 1 \\ \partial Q(z^{-1}) &= \partial A(z^{-1}) - 1 \end{aligned}. \tag{49}$$

The equation (48) is also condition for stability of closed loop system. Equation (47) can be simplified by using (48)

$$E(z^{-1}) = [1 - B(z^{-1})R(z^{-1})] W(z^{-1}), \tag{50}$$

and $W(z^{-1})$, that describes time continuous progress of control value, can be written as

$$W(z^{-1}) = \frac{N_w(z^{-1})}{D_w(z^{-1})} \tag{51}$$

A simplification of (50) is possible if

$$S(z^{-1}) = \frac{1 - B(z^{-1})R(z^{-1})}{D_w(z^{-1})}, \tag{52}$$

that can be rewritten into equation

$$D_w(z^{-1})S(z^{-1}) + B(z^{-1})R(z^{-1}) = 1 \tag{53}$$

with solution

$$\begin{aligned} \partial R(z^{-1}) &= \partial D_w(z^{-1}) - 1 \\ \partial S(z^{-1}) &= \partial B(z^{-1}) - 1 \end{aligned}. \tag{54}$$

The polynomial $S(z^{-1})$ is not necessary to calculate during a control process, but it can be used for the error calculation. Equations (49) and (54) can be solved by the indefinite coefficient method. The algorithm is used for a $W(z^{-1})$ tracking that must be known in advance. Practically steps are used, which can be written as

$$W(z^{-1}) = \frac{N_w(z^{-1})}{D_w(z^{-1})} = \frac{w_1}{1 - z^{-1}}. \tag{55}$$

The control step is considered as $w_1 = 1$ for next simplification. Next, the equation (53) can be written as

$$(1 - z^{-1})S(z^{-1}) + B(z^{-1})R(z^{-1}) = 1. \tag{56}$$

According to (54), polynomial $R(z^{-1})$ has zero degree and as a solution of (56) is

$$r_0 = \frac{1}{b_1 + b_2 + \ldots + b_n}. \tag{57}$$

A solution of Diophantine equation (48) for the second order system (1) leads to a system of matrixes

$$\begin{bmatrix} b_1 & 0 & 1 \\ b_2 & b_1 & a_1 \\ 0 & b_2 & a_2 \end{bmatrix} \begin{bmatrix} q_0 \\ q_1 \\ p_1 \end{bmatrix} = \begin{bmatrix} -a_1 \\ -a_2 \\ 0 \end{bmatrix} \tag{58}$$

The controller output can be described by

$$u(k) = r_0 w(k) - q_0 y(k) - q_1 y(k-1) - p_1 u(k-1) \tag{59}$$

where r_0 is calculated by

$$r_0 = \frac{1}{b_1 + b_2} \tag{60}$$

IV. Controller Hardware

The adaptive polynomial controller was implemented on a special hardware developed specially for limited space inside dryer. The hardware includes separate double-sided boards with main board, communication parts, power circuits providing heating control and HMI boards (displays, switches and theirs interfaces).The main board includes general purpose 8-bit microcontroller MC9S08DZ60 on 40MHz core frequency (20MHz bus clock), 4kb RAM and 60kb of flash memory for data program [6], power supplies (+5V, 3.3V, 3.6V for displays and 4.096V as reference voltage for temperature measurement), a backup battery for a RTC and a memory with last measured data (actual drying time, needed time to reach set temperature, time of a last power failure). An analog part measuring the temperature is also included on the main board. The temperature is measured at two positions in the dryer chamber with purpose of avoid local overheating. These temperatures are compared and a higher value is used by the controller. The temperature measuring is provided by Pt1000 sensors and 16-bit AD converter [7]. This form provides a high resolution. A comparative method was chosen for measuring voltage on Pt1000 sensors, because it needs only one precious (0.01%) and temperature stable (5ppm/°C) resistor. If a resistor value is properly selected, the voltage can be easily determined and converted to the temperature. The price of the system is lower than the other method is used and it is not increased by high price of high amount of precious and temperature stable components (resistors, AD converters, voltage references).

Although the connection on Fig. 3 is simple, there can be problem with measurement resolution. It is caused by a independently changing value of the Pt1000 sensors that are connected into series. Two of them are changing together, because they are in drying chamber, and the third measures internal temperature of electronic. In addition, the stable reference resistor is connected in that series.

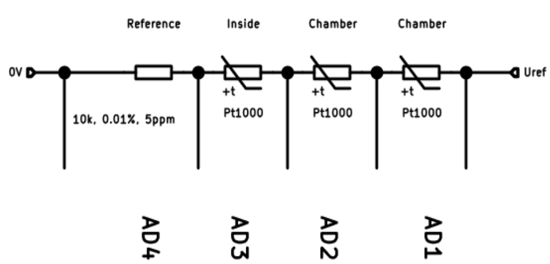

Fig. 3 Pt1000 connection

The resolution of the temperature measurement can be easily increased by changing a multiplier inside AD converter. It can be se to in four steps (1x, 2x, 4x, 8x) according to a voltage on Pt1000. However, it needs one more measurement (maximal three more in rapid temperature change) that can be delayed according to other values.

Fig. 2 Overview of the main controller board

V. Verification of the Controller

The adaptive controller was verified on real device at changing ambient conditions (temperature differences at 20°C, different air flow). First, the step responses were measured and next the controller was verified.

The verification was realized by connection through RS232 interface. The actually measuerd temperature, controller output and set value were sent each ones second. The period of PWM output signal was was chosen $T_{PWM} = 5s$ (100 times of AC line period), because the output signal is generated by solid state relay with zero-cross detection circuit. Therefore, there are 200 levels of controller output, because zero-cross detector detects each half-period, which can be omitted. These reasons give minimal output value 0.5% of maximal level (it is 7W per 5seconds in our case). The controller period was chosen $T_C = 10s$ for testing purposes and $T_C = 5s$ for final application.

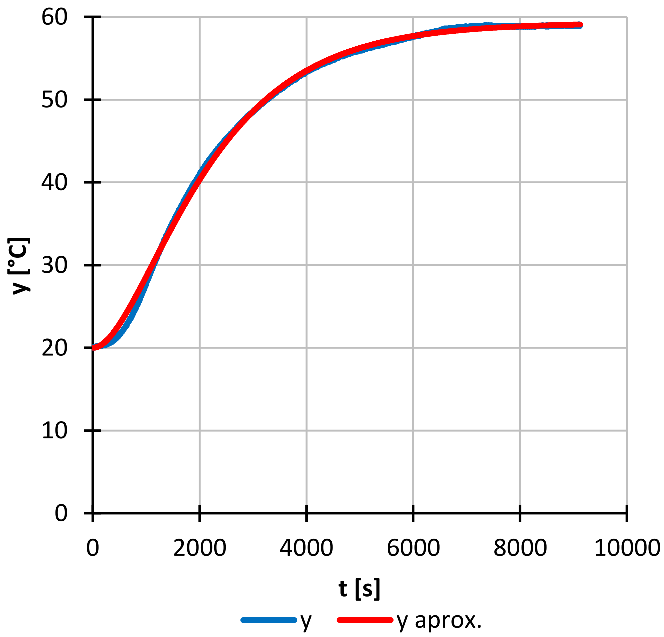

Fig. 4 System identification, u=3%

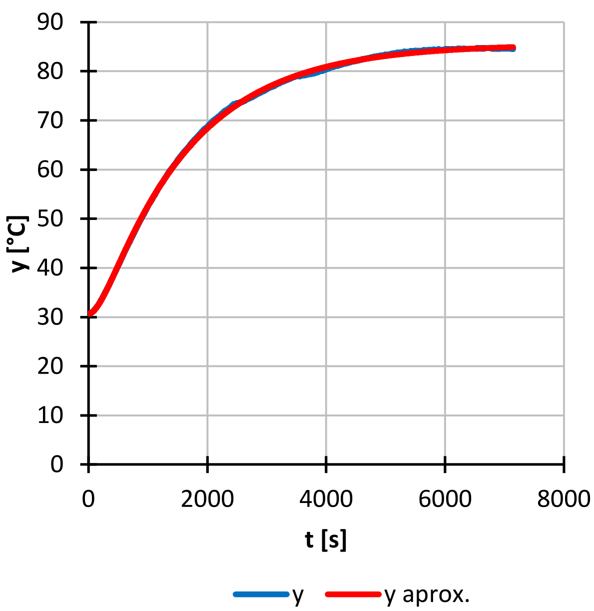

Fig. 5 System identification, u=5%

The first time identification of system was measured with $u_{OUT} = 3\%$ and $u_{OUT} = 5\%$ in order to the dryer not to be damaged by a high temperature. Step responses of both measurements are shown on Fig. 4 and Fig. 5.

The continues step responses were calculated for these measurements and they are written below (equation (61) corresponds to u=3%; (61) corresponds to u=5%). There can be seen some diferences caused other measurement conditions (higher temperature in laboratory).

$$G(s) = \frac{39{,}2}{(1484{,}9s+1)(858{,}0s+1)} \tag{61}$$

$$G(s) = \frac{54{,}8}{(1523{,}6s+1)(209{,}7s+1)} \tag{62}$$

The controll processes are shown in Fig. 6 and Fig. 7 for w=50°C and 80°C. As can be seen in graphs, instability at the process start occurs. It is influenced by parameters idetentificating of unknow system. This trait can be removed by using other controller (PID, two-state) at start of identification process and switching them if identified parameters are stabilized [3].

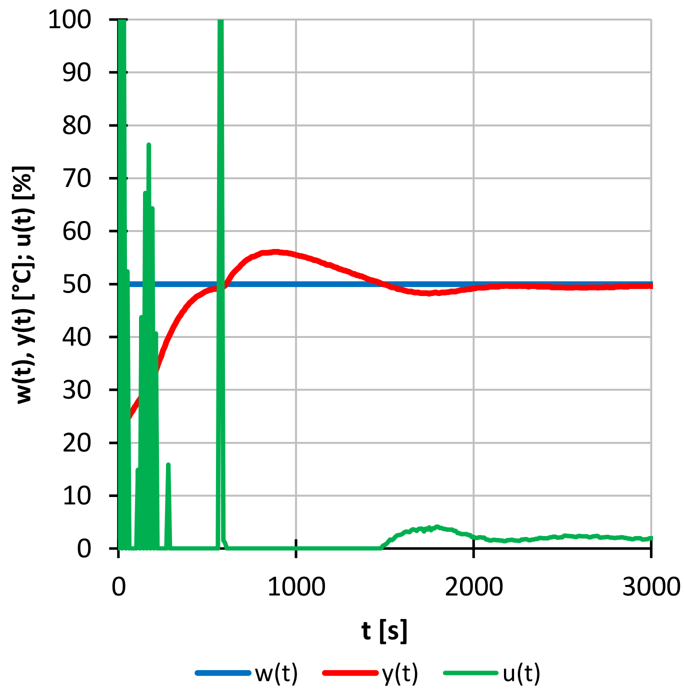

Fig. 6 Control process 1, w=50°C, T_c=10s

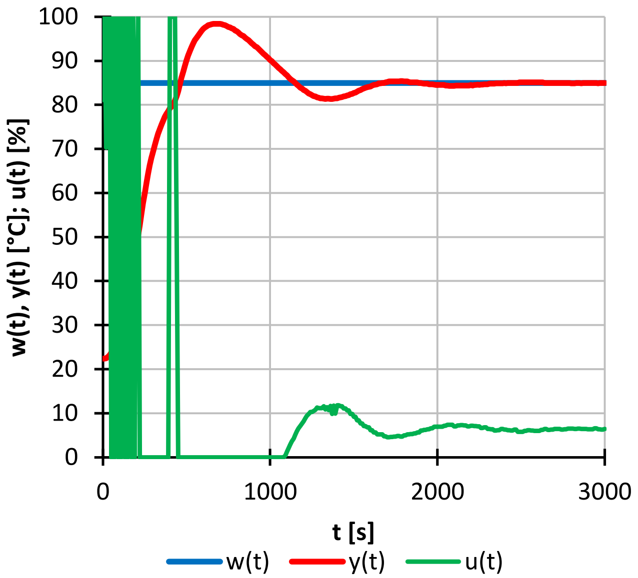

Fig. 7 Control process 2, w=85°C, T_c=10s

The controller was verified also with parameters obtained from controll proces 2 and switched adaptation off and changed period $T_C = 5s$. As can be seen on Fig. 8, the controll process has faster response to set value than process the controll process 2. In addition, there is no overshot, but stable controll error aproximatelly 1°C.

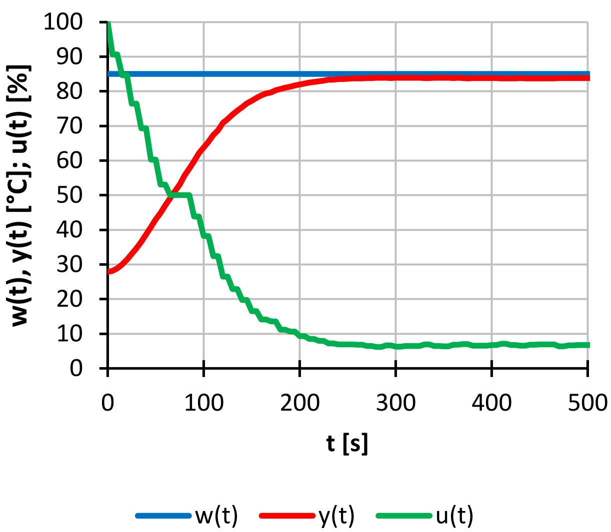

Fig. 8 Control process with switched adaptation off; w=85°C, T_c=5s

As a last graph is a measurement from real drying process. In the Fig. 9 only the first third of process is ploted (until temperature gets stable). There was some changes in dryer (added thermal insulation, mechanicals changes in chamber). In the controll procees a oscilattions of controler output occurred at time T=100s with duration aproximately T=150s. The stable controll error is casused by air vetilation through the dryer door, because it must be slightly opened to incrase quality of drying process.

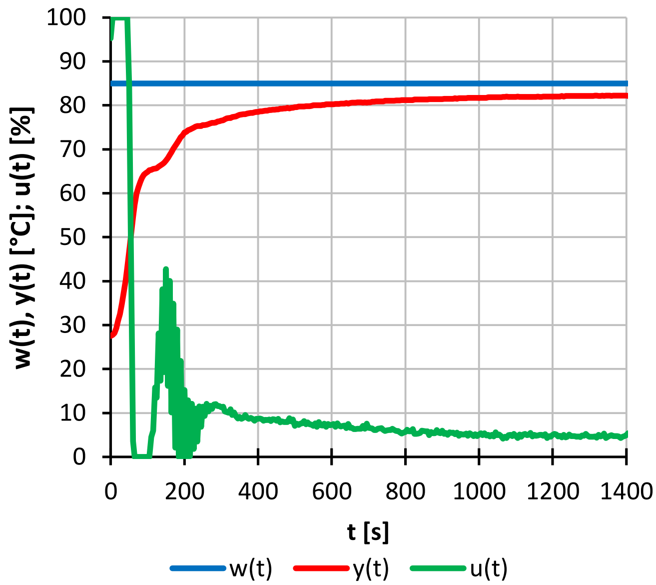

Fig. 9 Real control process , w=85°C, T_c=5s

VI. Conclusion

The article deals with the application of the adaptive polynomial controller to temperature regulation in the dryer chamber, which is used for production of printed circuit boards, especially for drying non-soldering mask and etch resist. The controller was implemented on base of 8-bit microcontroller intended for general and automotive sector. It proves sufficient performance of 8-bit microcontrollers, although controller needs high number of matrixes calculation and there can be used some 32-bit ARM microcontroller, which are massive used at present days. The design of device was universally conceptualized and the device can be used in other types of dryers. It is considered extension to oven for reflow soldering according to IPC/JEDEC standard [8].

The verification proves that adaptive controller can be used for real process, but the other measurements show that the parameters achieved by identification process may be used for controller without self-tuning part without any problems with stability or other unexpected situations.

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