Design of Multiloop Self-Tuning PID Controller and Experimental Evaluation on Injection Molding Machine

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Abstract

In this paper, a new multivariable self-tuning PID controller design scheme is proposed. The proposed control scheme has a static matrix pre-compensator in order to reduce the interaction terms of the process transfer function matrix. The static matrix pre-compensator is designed by priori *information. The $p \times p$ pre-compensated multivariate system is then controlled via 'p' univariate self-tuning PID controllers. The PID parameters are calculated on-line based on the relationship between the PID and generalized minimum variance control laws. The proposed scheme is experimentally evaluated on a 3×3 temperature control system. Experimental results illustrate the effectiveness of this new scheme.*

1. Introduction

Self-tuning control schemes[1],[2] are useful for systems with unknown or slowly time-varying parameters and represent a class of advanced control algorithms. On the other hand, PID[3]-[5] control algorithms still continue to be widely used for most industrial control systems, particularly in the chemical process industry. This is mainly because PID controllers have simple control structures, and are simple to maintain and tune. Therefore, it is still attractive to design discrete-time control systems with PID control structures. Furthermore, one may not be able to get good control performance in the case of time-varying processes. Many studies with auto-tuning[6]-[10] and self-tuning PID control[11]-[18] have been proposed. However, to the best of our knowledge, there are few studies of self-tuning PID control schemes for multivariable systems.

The main motivation in this study is to extend the univariate PID control scheme[18] to the multivariate control systems. Many industrial processes are inherently multivariate in nature and yet are presently controlled by multiloop PID control schemes, where the interaction among the loops is essentially ignored. The results of such control schemes are highly de-tuned loops and consequently often poor regulation and control.

This paper is organized as follows. The structure of a transfer function model to be considered in the estimation and design of control system is first considered, followed by a design scheme of the static matrix pre-compensator. Furthermore, based on the relationship between PID control and GMVC laws, a design scheme of multivariable self-tuning PID controllers is proposed. The proposed scheme is experimentally evaluated on a 3×3 computer-interfaced pilot-scale process.

2. Multivariable Self-Tuning PID Controller

2.1 Mathematical model

Let z^{-1} be the backward shift operator, then the following discrete-time p-input and p-output multivariable description of ARIMAX system describes the process:

$$\boldsymbol{A}(z^{-1})\boldsymbol{y}(t) = z^{-1}\boldsymbol{B}(z^{-1})\boldsymbol{u}(t) + \boldsymbol{d} + \boldsymbol{\xi}(t) \qquad (1)$$

where $\mathbf{u}(t)$ and $\mathbf{y}(t)$ are the input and output vector with p-elements, *i.e.*,

$$\left.\begin{array}{l} \mathbf{u}(t) = [u_1(t), u_2(t), \cdots, u_p(t)]^T \\ \mathbf{y}(t) = [y_1(t), y_2(t), \cdots, y_p(t)]^T, \end{array}\right\} \qquad (2)$$

and $\mathbf{x}(t)$ denotes the output of a white Gaussian noise vector through a disturbance transfer function vector. Δ is the differencing operator defined as $\Delta := 1 - z^{-1}$. Furthermore, $\mathbf{A}(z^{-1})$ is a polynomial matrix given by

$$\boldsymbol{A}(z^{-1}) = I + A_1 z^{-1} + A_2 z^{-2} \qquad (3)$$

with the coefficient matrix B_k is defined as

$$A_i = \begin{bmatrix} a_{i,1,1} & a_{i,1,2} & \cdots & a_{i,1,p} \\ a_{i,2,1} & a_{i,2,2} & \cdots & a_{i,2,p} \\ \vdots & \vdots & \ddots & \vdots \\ a_{i,p,1} & a_{i,p,2} & \cdots & a_{i,p,p} \end{bmatrix} \qquad (4)$$
$$(i = 1, 2).$$

$\mathbf{B}(z^{-1})$ is the following full polynomial matrix with elements:

$$\begin{aligned} \mathbf{B}(z^{-1}) &= \begin{bmatrix} B_{1,1}(z^{-1}) & B_{1,2}(z^{-1}) & \cdots & B_{1,p}(z^{-1}) \\ B_{2,1}(z^{-1}) & B_{2,2}(z^{-1}) & \cdots & B_{2,p}(z^{-1}) \\ \vdots & \vdots & \ddots & \vdots \\ B_{p,1}(z^{-1}) & B_{p,2}(z^{-1}) & \cdots & B_{p,p}(z^{-1}) \end{bmatrix} \\ &= B_0 + B_1 z^{-1} + \cdots + B_m z^{-m}, \end{aligned} \qquad (5)$$

with the coefficient matrix B_k is defined as

$$B_k = \begin{bmatrix} b_{k,1,1} & b_{k,1,2} & \cdots & b_{k,1,p} \\ b_{k,2,1} & b_{k,2,2} & \cdots & b_{k,2,p} \\ \vdots & \vdots & \ddots & \vdots \\ b_{k,p,1} & b_{k,p,2} & \cdots & b_{k,p,p} \end{bmatrix}$$
$$r(k = 1, 2, \cdots, m). \qquad (6)$$

D is the time-delay matrix of the form:

$$D = \mathrm{diag}\{z^{-k_{m_1}}, z^{-k_{m_2}}, \cdots, z^{-k_{m_p}}\}. \qquad (7)$$

k_{m_i} denotes the minimum value of estimated time-delays for the ith row. If the true time-delays, k_i, are known exactly in advance, it is better to set

$$k_{m_i} = \min_{j=1,\cdots,p} \{k_{i,j}\}, \qquad (8)$$

where $k_{i,j}$ denotes the time-delay between the i-th output and the j-th input signals. On the other hand, where the information about time-delays is not available, then k_{m_i} is set to 0. While the time-delay description in eqn.(7) may sound restrictive, in reality it is not because most real process have delay or interacter matrices of the diagonal form, or delays can be added to the actuators so that the delay matrix is of this diagonal form[20]. For the system (1), we make the following assumptions:

[Assumptions]

[A.1] The polynomial matrix $\mathbf{A}(z^{-1})$ is stable.

[A.2] The degree of $\mathbf{B}(z^{-1})$, m is known, and the following relationship is satisfied:

$$k_{m_i} \leq k_i \leq m \quad (i = 1, 2, \cdots, p). \qquad (9)$$

[A.3]$\mathbf{B}(1)$ is assumed to be non-singular.

[A.4] Reference input $w_i(t)$ consists of piecewise constant signals.

2.2 Pre-compensator

In designing multiloop controllers for multivariable control systems, it is important to first remove or compensate for interactions. The simplest pre-compensator that can be designed is a static parameter, H is with the form[21],[22]:

$$H := \mathbf{B}^{-1}(1)\mathbf{A}(1)$$
$$= \begin{bmatrix} h_{1,1} & h_{1,2} & \cdots & h_{1,p} \\ h_{2,1} & h_{2,2} & \cdots & h_{2,p} \\ \vdots & \vdots & \ddots & \vdots \\ h_{p,1} & h_{p,2} & \cdots & h_{p,p} \end{bmatrix} \qquad (10)$$

Such a pre-compensator essentially looks after the low frequency interaction. The augmented system constructed by eqns.(1) and (10) can then be described as

$$\mathbf{A}(z^{-1})\mathbf{y}(t) = D\mathbf{B}(z^{-1})H\mathbf{v}(t-1) + \mathbf{x}(t)/\Delta \quad (11)$$

where $\mathbf{v}(t)$ denotes the input signal vector to the augmented or pre-compensated system. In fact, the pre-compensator could be designed as $\mathbf{B}^{-1}(z^{-1})\mathbf{A}(z^{-1})$ in order to decouple the system exactly. However, this would be needlessly cumbersome for realization purposes and require the assumption that $\mathbf{B}(z^{-1})$ is asymptotically stable. Therefore, a simple static pre-compensator as given by eqn.(10) is used in this paper. This is the static approximation of $\mathbf{B}^{-1}(z^{-1})\mathbf{A}(z^{-1})$. The idea behind static decoupling is that diagonal dominance is a suitably weaker requirement in comparison with complete or strong decoupling, via dynamic pre-compensators, in the design of controllers for multivariate systems. In general, careful design of a static decoupler can achieve diagonal dominance. Many industrial processes are controlled in a multi-loop manner without any pre-compensation whatsoever.

By regarding the augmented system (11) as the approximately or almost decoupled system, the following model can be obtained for each diagonal element:

$$A_i(z^{-1})y_i(t) = z^{-k_{m_i}}\bar{B}_i(z^{-1})v_i(t-1) + x_i(t)/\Delta \quad (i = 1, 2, \cdots, p) \qquad (12)$$

where

$$\left.\begin{aligned} \bar{B}_i(z^{-1}) :&= \sum_{k=1}^{p} B_{i,k}(z^{-1})h_{k,i} \\ &= \bar{b}_{i,0} + \bar{b}_{i,1}z^{-1} + \cdots + \bar{b}_{i,m}z^{-m} \end{aligned}\right\} \qquad (13)$$

and $A_i(z^{-1})$ is given by eqn.(3).

$\boldsymbol{H}$ in eqn.(10) can be designed when $\boldsymbol{A}(z^{-1})$ and $\boldsymbol{B}(z^{-1})$ are known. However, it is difficult to obtain these parameters exactly. So, in this paper, $\boldsymbol{H}$ is calculated as follows.

First, the static value of $\boldsymbol{u}(t)$ and $\boldsymbol{y}(t)$ are defined as $\bar{\boldsymbol{u}}$ and $\bar{\boldsymbol{y}}$, respectively. Then, $\bar{\boldsymbol{y}}$ can be described as the following equation:

$$\bar{\boldsymbol{y}} = \bar{\boldsymbol{G}}\bar{\boldsymbol{u}} + \bar{\boldsymbol{d}}, \qquad (14)$$

where $\bar{\boldsymbol{G}}$ means the static gain matrix as

$$\bar{\boldsymbol{G}} := \boldsymbol{A}^{-1}(1)\boldsymbol{B}(1) \qquad (15)$$

and

$$\bar{\boldsymbol{d}} := \boldsymbol{A}^{-1}(1)\boldsymbol{d}. \qquad (16)$$

The following equation can be obtained by eqn.(14):

$$\begin{bmatrix} \bar{y} \\ 1 \end{bmatrix} = \begin{bmatrix} & \bar{G} & & \bar{d} \\ 0 & \dots & 0 & 1 \end{bmatrix} \begin{bmatrix} \bar{u} \\ 1 \end{bmatrix}. \tag{17}$$

Next, p-sets of independent data $\bar{\boldsymbol{u}}_1 \dots \bar{\boldsymbol{u}}_p$ and $\bar{\boldsymbol{y}}_1 \dots \bar{\boldsymbol{y}}_p$, are prepared in order to calculate $\bar{\boldsymbol{G}}$ and $\bar{\boldsymbol{d}}$ uniquely. Then, the following relationship can be obtained:

$$\bar{\boldsymbol{y}_a} = \bar{\boldsymbol{G}}_a \bar{\boldsymbol{u}_a}, \tag{18}$$

where

$$\left.\begin{aligned} \bar{\boldsymbol{y}_a} &= \begin{bmatrix} \bar{\boldsymbol{y}}_1 & \dots & \bar{\boldsymbol{y}}_p \\ 1 & \dots & 1 \end{bmatrix} \\ \bar{\boldsymbol{G}_a} &= \begin{bmatrix} & \bar{\boldsymbol{G}} & & \bar{\boldsymbol{d}} \\ 0 & \dots & 0 & 1 \end{bmatrix} \\ \bar{\boldsymbol{u}_a} &= \begin{bmatrix} \bar{\boldsymbol{u}}_1 & \dots & \bar{\boldsymbol{u}}_p \\ 1 & \dots & 1 \end{bmatrix} \end{aligned}\right\} \tag{19}$$

Therefore, $\bar{\boldsymbol{G}}_a$ can be derived as

$$\bar{\boldsymbol{G}_a} = \bar{\boldsymbol{y}_a}^{-1} \bar{\boldsymbol{u}_a}, \tag{20}$$

and the pre-compensator $\boldsymbol{H}$ can be designed by

$$\boldsymbol{H} = \bar{\boldsymbol{G}}^{-1} \tag{21}$$

It may be possible to get the static values $\bar{\boldsymbol{u}}_1 \dots \bar{\boldsymbol{u}}_p$ and $\bar{\boldsymbol{y}}_1 \dots \bar{\boldsymbol{y}}_p$ while controlling the controlled object. Then, $\boldsymbol{H}$ can be adjusted in an on-line manner.

2.3 Multiloop PID controller design

Next, we consider the design of PID controllers[18] for the augmented system given by eqn.(12). The digital PID control law to be considered in this paper is described as

$$\begin{aligned} \Delta v_i(t) = k_{c_i}[\{e_i(t) - e_i(t-1)\} + \frac{T_s}{T_{I_i}} e_i(t) \\ + \frac{T_{D_i}}{T_s}\{e_i(t) - 2e_i(t-1) + e_i(t-2)\}] \end{aligned} \tag{22}$$

where $e_i(t)$ denotes the control error signal given by

$$e_i(t) := w_i(t) - y_i(t) \tag{23}$$

and k_{c_i}, T_{I_i} and T_{D_i} are the proportional gain, the reset time and the derivative time, respectively. Furthermore, T_s denotes the sampling interval. For convenience, let $L_i(z^{-1})$ be

$$\begin{aligned} L_i(z^{-1}) := k_{c_i}(1 + \frac{T_s}{T_{I_i}} + \frac{T_{D_i}}{T_s}) - k_{c_i}(1 + \frac{2T_{D_i}}{T_s})z^{-1} \\ + \frac{k_{c_i} T_{D_i}}{T_s} z^{-2} \end{aligned} \tag{24}$$

then, eqn.(22) can be rewritten by

$$L_i(z^{-1})y_i(t) + \Delta v_i(t) - L_i(z^{-1})w_i(t) = 0. \tag{25}$$

The tuning of the control constants in PID control laws (22) or (25), is important, since the performance of the control system strongly depends on them. For systems with unknown parameters and unknown time-delays, however, it is difficult to easily find the "optimal" PID parameters. Therefore a self-tuning PID control algorithm based on the relationship between PID control and generalized minimum variance control(GMVC) laws, is derived below.

2.4 PID tuning

Consider the following cost function to derive a GMVC control law:

$$J_i = E[\phi_i^2(t + k_{m_i} + 1)]. \tag{26}$$

$\phi_i(t+k_{m_i}+1)$ in eqn.(26) denotes the generalized output of the form:

$$\begin{aligned} \phi_i(t + k_{m_i} + 1) := P_i(z^{-1})y_i(t + k_{m_i} + 1) + \lambda_i \Delta v_i(t) \\ - R_i(z^{-1})w_i(t), \end{aligned} \tag{27}$$

where λ_i in eqn.(27) is the weighting factor with respect to the control input, $P_i(z^{-1})$ is the user-specified design polynomial of the form:

$$P_i(z^{-1}) = 1 + p_{i,1}z^{-1} + p_{i,2}z^{-2}, \tag{28}$$

and $R_i(z^{-1})$ is determined based on the relationship between PID control and GMVC laws. The control input minimizing the cost function (26) is given by the following equation[2]:

$$\begin{aligned} F_i(z^{-1})y_i(t) + \{E_i(z^{-1})\bar{B}_i(z^{-1}) + \lambda_i\}\Delta v_i(t) \\ - P_i(1)w_i(t) = 0 \end{aligned} \tag{29}$$

where $E_i(z^{-1})$ and $F_i(z^{-1})$ are obtained by solving the following Diophantine equation:

$$P_i(z^{-1}) = \Delta A_i(z^{-1})E_i(z^{-1}) + z^{-(k_{m_i}+1)}F_i(z^{-1}) \tag{30}$$

$$\left.\begin{aligned} E_i(z^{-1}) &= 1 + e_{i,1}z^{-1} + \dots + e_{i,k_{m_i}}z^{-k_{m_i}} \\ F_i(z^{-1}) &= f_{i,0} + f_{i,1}z^{-1} + f_{i,2}z^{-2}. \end{aligned}\right\} \tag{31}$$

Next, based on the relationship between PID control and GMVC laws, a tuning method of PID parameters is derived. Usually the dynamics of the system to be controlled, for example the time-delays or the time constants, are rarely known precisely in advance. In particular, knowledge of the delay is important. Here, we adopt the strategy that k_{m_i} be under estimated *i.e.*, initially use the upperbound estimate of the delay, or assume that the order of $\bar{B}_i(z^{-1})$ is large enough, in order to cope with the above problem. Therefore, the estimates k_{m_i} and $\bar{B}_i(z^{-1})$, *i.e.*, the second term $E_i(z^{-1})\bar{B}_i(z^{-1})$ in eqn.(29) includes some uncertainties. In order to obtain a control law with a PID structure, we consider the following equation with $E_i(z^{-1})\bar{B}_i(z^{-1})$ replaced by the static gain $E_i(1)\bar{B}_i(1)$:

$$F_i(z^{-1})y_i(t)+\{E_i(1)\bar{B}_i(1)+\lambda_i\}\Delta v_i(t)-R_i(z^{-1})w_i(t)=0. \tag{32}$$

Here, ν_i is defined as

$$\nu_i := E_i(1)\bar{B}_i(1)+\lambda_i \tag{33}$$

then, eqn.(32) can be rewritten as

$$\frac{F_i(z^{-1})}{\nu_i}y_i(t)+\Delta v_i(t)-\frac{R_i(z^{-1})}{\nu_i}w_i(t)=0. \tag{34}$$

Furthermore, if the following relations are satisfied:

$$\left.\begin{aligned} R_i(z^{-1}) &= F_i(z^{-1}) \\ L_i(z^{-1}) &= \frac{F_i(z^{-1})}{\nu_i} \end{aligned}\right\} \tag{35}$$

as in eqn.(34), then eqn.(34) becomes identical to eqn.(25). Therefore, based on eqns.(24) and (35), the PID parameters can be calculated as follows:

$$\left.\begin{aligned} k_{c_i} &= -\frac{1}{\nu_i(f_{i,1}+2f_{i,2})} \\ T_{I_i} &= -\frac{f_{i,1}+2f_{i,2}}{f_{i,0}+f_{i,1}+f_{i,2}}T_s \\ T_{D_i} &= -\frac{f_{i,2}}{f_{i,1}+2f_{i,2}}T_s. \end{aligned}\right\} \tag{36}$$

Note that the parameters λ_i are related to only k_{c_i}. In other words, T_{I_i} and T_{D_i} are independent of λ_i. Thus, the proposed scheme has a feature such that after selecting $P_i(z^{-1})$ in the generalized output (27), λ_i can be determined or chosen independently by considering the stability of the control system based on *a priori* information.

2.5 Self-tuning controller

Based on the control scheme discussed above, a multivariable self-tuning PID control is designed in this section.

The unknown parameters included in the augmented system (12) are estimated via the following RLS algorithm:

$$\begin{aligned} \hat{\theta}_i(t) =& \hat{\theta}_i(t-1) \\ &+\frac{\Gamma_i(t-1)\psi_i(t-1)}{1+\psi_i^T(t-1)\Gamma_i(t-1)\psi_i(t-1)}\varepsilon_i(t) \end{aligned} \tag{37}$$

$$\begin{aligned} \Gamma_i(t) =& \frac{1}{\omega_2}\left[\Gamma_i(t-1)\right. \\ &\left.-\frac{\Gamma_i(t-1)\psi_i(t-1)\psi_i^T(t-1)\Gamma_i(t-1)}{\omega_2+\psi_i^T(t-1)\Gamma_i(t-1)\psi_i(t-1)}\right] \end{aligned} \tag{38}$$

$$\varepsilon_i(t)=\Delta y_{g_i}(t)-\hat{\theta}_i^T(t-1)\psi_i(t-1)(i=1,2,\cdots,p) \tag{39}$$

where ω is a forgetting factor with limits: $0<\omega\le 1$, and $\varepsilon_i(t)$ is a prediction error. $\hat{\theta}_i(t)$ and $\psi_i(t-1)$ are given by

$$\hat{\theta}_i(t)=[\hat{a}_{i,1}(t),\hat{a}_{i,2}(t),\hat{\bar{b}}_{i,0}(t),\hat{\bar{b}}_{i,1}(t),\cdots,\hat{\bar{b}}_{i,m}(t)]^T \tag{40}$$

$$\begin{aligned} \psi_i(t-1)=&[-\Delta y_{g_i}(t-1),-\Delta y_{g_i}(t-2), \\ &\Delta v_{g_i}(t-k_{m_i}-1),\cdots, \\ &\Delta v_{g_i}(t-k_{m_i}-m-1)]^T. \end{aligned} \tag{41}$$

For the purpose of improving reliability of the parameter estimation and once again emphasizing estimation accuracy at lower frequencies, the following estimator filter $C(z^{-1})$ is also utilized.

$$C(z^{-1}) := \frac{1-c}{1-cz^{-1}} \tag{42}$$

Therefore, y_{g_i} and vg_i included in (39) and (41) are given by

$$\left.\begin{aligned} y_{g_i}(t) &:= C(z^{-1})y_i(t) \\ v_{g_i}(t) &:= C(z^{-1})v_i(t). \end{aligned}\right\} \tag{43}$$

By solving the Diophantine equation (21) based on estimates included in $\hat{\theta}(t)$, and calculating eqns.(24) and (27), PID parameters can be obtained.

A block diagram of the multivariable self-tuning PID control system is shown in **Fig.1**.

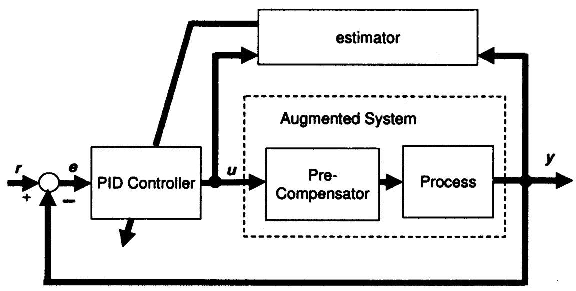

Fig. 1. Brock diagram of control system.

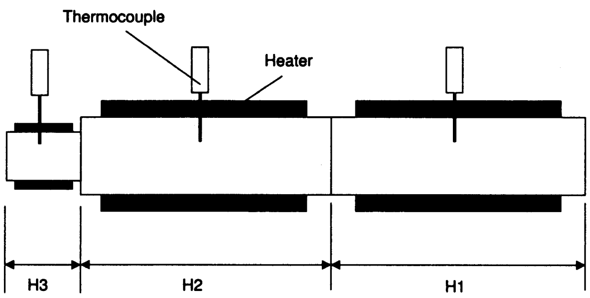

Fig. 2. Schematic diagram of the control system.

The proposed multivariable self-tuning PID control algorithm is then realized via the following steps.

[Multivariable Self-Tuning PID control algorithm]

1. Calculate the pre-compensator H based on eqn.(10).
2. Choose $P_i(z^{-1})$ and λ_i.
3. Design the estimator filters $C(z^{-1})$.
4. Estimate $\hat{\theta}_i(t)$ by using the RLS algorithm in eqns.(37)-(41).
5. Solve the Diophantine equation (30).
6. Calculate ν_i based on eqn.(33).
7. Calculate PID parameters based on eqn.(27).
8. Calculate the control input vector $\mathbf{u}(t)$ based on eqn.(22).
9. Update t and return to 4.

3. Experimental Results

In this section, the proposed self-tuning controller is experimentally evaluated on a pilot-scale temperature control system. The schematic diagram of the equipment is shown in **Fig.2**.

This temperature control system had been made to imitate heating barrels in the injection molding machine. This system consists of three zone. Each zone have a thermocouple as the sensor of temperature and a heater as the actuator.

The control objective is to regulate the temperature of the zone 1, y_1, the zone 2, y_2 and the zone 3, y_3, by manipulating the control valves, u_1, u_2 and u_3. The system is highly coupled.

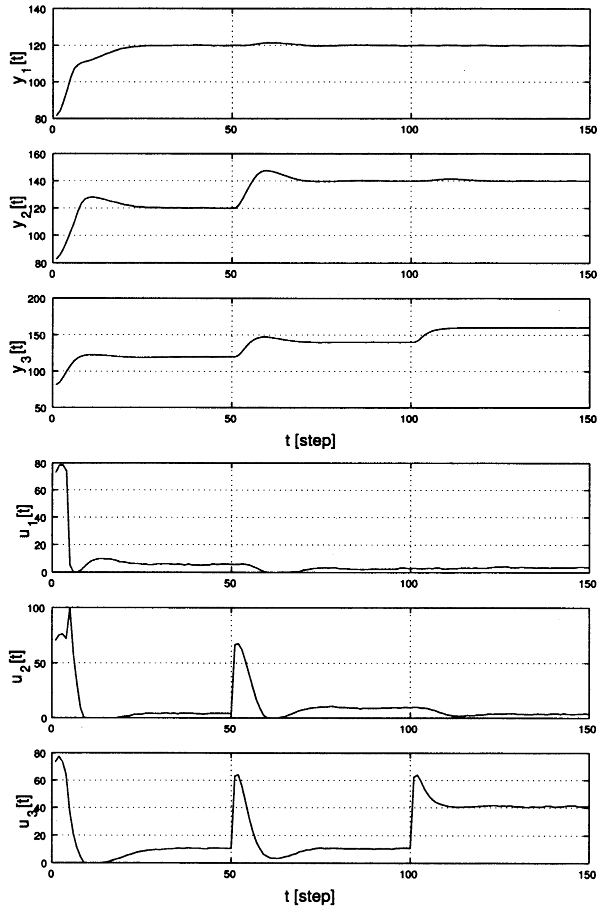

Fig. 3. Control result by proposed method.

The transfer function elements of the process can be approximated as the first-order system with time-delays. The multivariable PI control system is then constructed with $a_{i,2}$=0 in eqn.(4). The sampling interval is set to 30[sec].

The result of using the proposed control scheme is shown in **Fig.3**, where $P_i(z^{-1})$ and λ_i are set to $P_i(z^{-1}) = 1 - 1.43z^{-1} + 0.51z^{-2}$ and $\lambda_i = 0.1$.

4. Conclusions

In this paper, a design scheme of multivariable self-tuning PID controllers has been proposed. The main features of the proposed control scheme are summarized as follows.

- A practical self-tuning design strategy for multivariable systems, that is based on the classical Nyquist array techniques, has been presented.
- In order to cope with the interaction of the system, a static pre-compensator is designed by the inverse of the estimated static gain matrix of the system.

- The control algorithm has a parameter estimator which work for the on-line tuning of the PID parameters.

- For the purpose of improving the reliability of the parameter estimator, simple exponential type data pre-filters are used to condition the signals prior to estimation.

- PID parameters are calculated based on the relationship between PID control and GMVC laws.

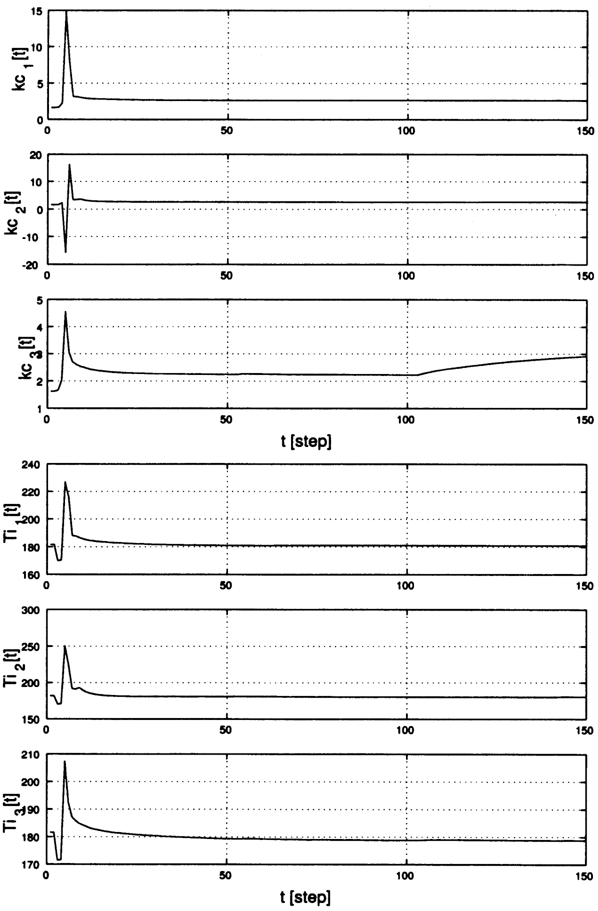

Fig. 4. PI parameters trajectory.

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