NEW TUNING METHOD FOR PID CONTROL OF A PLANT WITH UNDER-DAMPED RESPONSE

Jing-Chung Shen

ABSTRACT

In this paper, a tuning formula is derived for PID control of plants with under-damped step responses. The under-damped systems are modeled by second-order plus dead time transfer functions. To derive the tuning rule, the dominant pole assignment method was applied to design the PID controllers for a variety of plant models. Then, the correlation between the controller parameters and the parameters of the models was found and the tuning formula derived. Several simulation examples are given to demonstrate the effectiveness and robustness of this formula.

KeyWords: PID controller, auto tuning, under-damped systems, dominant pole assignment.

I. INTRODUCTION

The proportional-integral-derivative (PID) controllers are based on the most common control algorithm [6]. Due to their simplicity and robustness, the PID controllers are widely used [1]. There are many tuning formulas for PID and PI control for plants with over-damped step responses [1-7,9-12,14-16]. Recently, Ho et al. [8] and Wang et al. [13] proposed new tuning methods for PID controllers for plants that have under-damped step responses. The method proposed by Ho et al. is based on gain margin (GM) and phase margin (PM) specifications. They introduced some approximations into the calculation and derived a tuning formula. The method in [13] is based on the closed-loop pole allocation strategy through use of the root-locus. However, the effectiveness of PID controllers is not well understood for plants with under-damped step responses as indicated in [8].

It is known that the dominant pole assignment method is a reliable design method for PID control [2]. However, this design problem needs to be solved by using a numerical method. In [2], the authors utilized the dominant pole assignment method to derive a tuning method for PID and PI controllers for plants with over-damped step responses. They applied the dominant pole assignment method to a batch of test plants and then found simple formulas that describe the correlation between the process characteristics and the controller parameters. In this study, we utilized the same technique to derive a new tuning formula for PID control of plants with under-damped step responses. Simulation of various example cases shows that this new formula gives satisfactory results.

This paper is organized as follows: In Section 2, the dominant pole assignment method is described and a way to derive the tuning formula is proposed. Examples are given in Section 3 to show the effectiveness and robustness of the formula. Conclusions are given in Section 4.

II. THE TUNING FORMULA

To derive the new tuning formula, one batch of test plant models was chosen to represent plants with under-damped step responses. Then, the dominant pole assignment method was applied to design the PID controllers for the plant models in this test batch. We then derived the tuning formula by finding simple formulas that described the correlation between the plant parameters and the controller parameters.

This method is based on the dominant pole assignment method. Therefore, the dominant pole assignment method is reviewed briefly in the next subsection; for more details, please refer to [2] and the references therein.

2.1. Dominant pole assignment method

Let the PID controller be implemented as follows:
\[ u = K(e + \frac{1}{T_i} \int e \, dt + T_d \frac{de}{dt}) \]

\[ e = y_r - y, \]  \hspace{1cm} (1) \]

where \( u \), \( y \), and \( y_r \) are the controller output, the set point and the plant output, respectively. The under-damped systems are modeled by the transfer function

\[ G_y(s) = \frac{Y(s)}{U(s)} = \frac{\alpha \omega_n e^{-\alpha t}}{s^2 + 2\xi \omega_n s + \omega_n^2} , \quad 0 < \xi < 1. \]  \hspace{1cm} (2) \]

The transfer function of the controller is

\[ G_c(s) = \frac{U(s)}{E(s)} = K(1 + \frac{1}{sT_i} + sT_d) = K + \frac{K_d}{s} + K_is. \]  \hspace{1cm} (3) \]

Note that there are three parameters in the PID controller, and that three of the closed-loop system can be assigned. Let the assigned poles be \( P_1 = \omega_n(\xi_0 \pm i\sqrt{1 - \xi_0^2}) \) and \( P_2 = -\alpha \omega_n \). Denote \( G_y(P_1) = re^{\theta} \), \( G_y(P_2) = -\kappa \), and \( \theta = \cos^{-1}(\xi_0) \). Then \( K, K_d, K_i \) and \( \alpha \) can be determined by solving the following equation:

\[
\begin{bmatrix}
\kappa \\
\frac{-\kappa}{\omega_n} \\
-\alpha \omega_n \kappa \\
-\alpha \omega_n \\
-\alpha \omega_n \cos(\phi + \theta) \\
-\alpha \omega_n \sin(\phi + \theta) \\
-\alpha \omega_n \cos(\phi - \theta) \\
-\alpha \omega_n \sin(\phi - \theta)
\end{bmatrix}
\begin{bmatrix}
K \\
K_i \\
K_d
\end{bmatrix}
= \begin{bmatrix}
1 \\
1 \\
0
\end{bmatrix}.
\]

Let \( M_s \) denote the maximum sensitivity, i.e.,

\[ M_s = \max \left \{ \frac{1}{1 + G_y(j\omega)G_c(j\omega)} \right \}. \]

Note that \( M_s \) is a robustness measure for stability. Suppose that \( e_d \) is the error caused by a unit step disturbance at the process input and define the integrated error IE as

\[ IE = \int_0^\infty e_d(t) \, dt. \]

The design goal of the dominant pole assignment method is to select \( \xi_0, \omega_n \), and \( \alpha \) such that IE is minimized under the constraint that \( M_s \) is equal to a prescribed value. Typical values of \( M_s \) fall in the range from \( 1.4 \) to \( 2.0 \). The standard value is \( M_s = 2.0 \) [2]. In this paper, the standard value is used. Clearly, this design problem must be solved by using a numerical method. For convenience, the design procedure is described as follows:

1) Select \( \xi_0 \).
2) Search \( \alpha \) and \( \omega_n \) such that the integrated error IE is minimized.
3) Compute \( M_s \) and check its value. If \( M_s \) equals the prescribed value, then stop; else, adjust the value of \( \xi_0 \), \( \alpha \), and \( \omega_n \) and go to step 2.

From the procedure described above, it can be seen that the PID controller is chosen by considering the stability robustness requirement and the load disturbance response of the system. It is well known that set-point weighting is useful in shaping the responses of the set point changes. To improve the set point response of the system, a set-point weighting \( b \) is introduced into the PID controller as

\[ u = K((by_r - y) + \frac{1}{T_i} \int e \, dt + T_d \frac{de}{dt}). \]  \hspace{1cm} (4) \]

In this paper, the set-point weighting \( b \) is determined based on the rules proposed in [2].

2.2. Deriving the tuning formula

To derive the new tuning formula, a batch of test plant models must be chosen. The plant models in this test batch should be able to represent the under-damped plants that can be controlled reasonably well by PID controllers. In [8], Ho et al. indicated that plants with a large dead time (large \( L \)) or a large natural frequency (large \( \omega_n \)) (plants with \( \omega_n L > 1 \)) should be controlled using a more advanced controller. In this study, we chose plant models randomly from a wider range (\( \omega_n L \leq 15 \)). Table 1 lists \( \omega_n \) and \( L \) that were chosen. The plant models with \( \xi = 0.1, 0.2, \ldots, 0.9 \), \( \omega_n \), and \( L \) listed in Table 1 were used in this study.

Table 1. \( \omega_n \) and \( L \) of the plant models.

<table>
<thead>
<tr>
<th>No.</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
<th>11</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \omega_n )</td>
<td>0.1</td>
<td>1.0</td>
<td>0.5</td>
<td>0.2</td>
<td>0.1</td>
<td>2.0</td>
<td>0.1</td>
<td>5.0</td>
<td>2.0</td>
<td>0.3</td>
<td>1.0</td>
</tr>
<tr>
<td>( L )</td>
<td>0.5</td>
<td>0.1</td>
<td>0.4</td>
<td>1.3</td>
<td>3.0</td>
<td>0.2</td>
<td>5.0</td>
<td>0.13</td>
<td>0.4</td>
<td>3.0</td>
<td>1.0</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>No.</th>
<th>12</th>
<th>13</th>
<th>14</th>
<th>15</th>
<th>16</th>
<th>17</th>
<th>18</th>
<th>19</th>
<th>20</th>
<th>21</th>
<th>22</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \omega_n )</td>
<td>0.2</td>
<td>3.0</td>
<td>0.6</td>
<td>6.0</td>
<td>2.0</td>
<td>8.0</td>
<td>1.0</td>
<td>3.0</td>
<td>2.0</td>
<td>4.0</td>
<td>3.0</td>
</tr>
<tr>
<td>( L )</td>
<td>6.0</td>
<td>0.5</td>
<td>3.0</td>
<td>0.4</td>
<td>1.5</td>
<td>0.5</td>
<td>5.0</td>
<td>2.0</td>
<td>4.0</td>
<td>3.0</td>
<td>5.0</td>
</tr>
</tbody>
</table>
Once the models were chosen, the dominant pole assignment method could be applied to design a PID controller for each plant model. There were 198 models in the test batch. Therefore, it took a lot of time to perform the whole process.

Next the correlation between the controller parameters and the parameters that characterized the plant dynamics was found. Firstly, the parameters that characterized the plant dynamics had to be selected. For plants with over-damped step responses and those modeled using a first order plus dead time transfer function \( K e^{-a_s I/(1 + sT)} \), \( a_s = L_a/T \) (the ratio of the apparent dead time to the apparent time constant) or \( L_a/(T + L_a) \) (the normalized dead time) was used to characterize the plants [2]. Therefore, we could utilize \( a_u = \xi \omega_n L \) (the ratio of the apparent dead time \( L \) to the equivalent time constant \( 1/\xi \omega_n \)) or \( \tau_a = L/(L + (1/\xi \omega_n)) = a_u/(1 + a_u) \) to characterize plants with under-damped step responses.

In [8] the authors utilized the term \( a = \omega_n L \) to characterize the plants. Thus, \( \tau = a/(1 + a) \) can be used too. It is also known that the damping ratio \( \xi \) is an important parameter for under-damped plants. In another report [13], the authors did utilize \( \xi \) and \( a_u \) to characterize the plants. Note that \( 1 < \xi < 1 \), \( \tau_u \) and \( \tau \) also have this property. Therefore, \( \xi \) and \( \tau_u \) or \( \xi \) and \( \tau \) were selected to characterize the plants. Note that these parameters are dimension-free. Thus, the parameters of the controller can also be represented in a dimension-free form by means of normalization. For plants with over-damped responses, the controller parameters are normalized as \( a K, T_i/L \) and \( T_d/L \) [2]. In this study, the controller parameters were normalized as \( a K, T_i/L \) and \( T_d/L \).

After these parameters were chosen, an empirical method was used to find the relations between the normalized controller parameters and the parameters that characterized the plants. The normalized controller parameters were plotted as functions of \( \xi \) and \( \tau_a \) or \( \xi \) and \( \tau \). We then investigated whether the normalized controller parameters could be expressed as functions of \( \xi \) and \( \tau_u \) or of \( \xi \) and \( \tau \). Fig. 1 and Fig. 2 show the results of plotting.

The curves in Fig. 2 are smoother than the curves in Fig. 1. Therefore, Fig. 2 was used to find the tuning formula. We tried to express the normalized controller gain as

\[
a K = f(\xi, \tau)
\]

and analogous expressions for other parameters by means of curve fitting. In Fig. 2, the variation of the normalized controller parameters is large for the plants.

---

**Fig. 1.** Controller parameters for PID control of the plants listed in Table 1. (\( \xi = 0.1: +, \xi = 0.2: \odot, \xi = 0.3: *, \xi = 0.4: \bullet, \xi = 0.5: x, \xi = 0.6: \square, \xi = 0.7: \diamondsuit, \xi = 0.8: \Delta, \xi = 0.9: \triangledown).**
with parameters in the range \( \tau > 0.5 (\omega_n L > 1) \) and \( \xi < 0.4 \). This makes it difficult to do curve fitting. Plants in this range are those with large dead time \((L)\), large undamped natural frequency \((\omega_n)\), or poor damping \(\xi < 0.4\), so a controller more advanced than the PID controller may have to be considered. Therefore, we abandoned these data and separated the plants into two groups \((0 < \tau \leq 0.5, 0 < \xi < 1\) and \(0.5 < \tau < 1, 0.4 \leq \xi < 1)\) for curve fitting.

The scale of the \(y\)-axis in Fig. 2 is logarithmic. Therefore, the function is presented in exponential form. Let

\[
 f(\xi, \tau) = \exp(g(\xi, \tau)),
\]

where \(g(\xi, \tau)\) is a polynomial. After some trials, we found that the functions could be well approximated by functions of the form

\[
 f(\xi, \tau) = \exp \left( a_0 + a_1 \tau + a_2 \tau^2 + a_3 \xi + a_4 \xi^2 + a_5 \tau \xi + a_6 \tau^2 \xi + a_7 \tau \xi^2 + a_8 \tau^2 \xi^2 + a_9 \tau^3 \xi + a_{10} \tau^4 \xi + a_{11} \tau^5 \xi \right).
\]

Table 2 shows the coefficients \(a_0, a_1, \ldots, a_{11}\) of the functions of the form (5) that were least squares fitted to the data in Fig. 2. The surfaces obtained are plotted in Fig. 3 and Fig. 4.

Figure 5 and Fig. 6 show the fitting errors. From Fig. 5(a)-(d), we find that the fitting errors are within \(\pm 20\%\) for the plants in the range \(0 < \tau \leq 0.5, 0 < \xi < 1\). Figures 6(a)-(c) show that the fitting errors of \(aK, T_i/L\) and \(T_d/L\) are also within \(\pm 20\%\) for the plants in the range \(0.5 < \tau < 1, 0.4 \leq \xi < 1\). Figure 6(d) shows that the fitting errors of \(b\) are still inside \(\pm 20\%\) for small \(\tau\), but that the errors become large as \(\tau\) increases. The fitting errors can be decreased further if the order of the polynomial in (5) is increased. However, the results of simulation studies show that the formula listed in Table 2 is good enough.

### III. SIMULATION EXAMPLES

In order to demonstrate the effectiveness and robustness of new tuning formula, we applied it to a few plants. Comparisons will be made with results obtained by Ho using a gain and phase margin method [8] and those obtained using the latest method proposed by
Wang et al. [13]. The plant model for the proposed method is determined through a step response experiment (see [2] for details). The dead time $L$ is obtained by determining the time between the onset of the step and the time when the step response reaches 2% of its final value. In Wang’s method [13], the plant is modeled by the following equations:

\[ \log_{10} \left( aK \right) \text{ vs. } \tau, \xi \\
\log_{10} \left( T_i / L \right) \text{ vs. } \tau, \xi \\
\log_{10} \left( T_d / L \right) \text{ vs. } \tau, \xi \\
\log_{10} \left( b \right) \text{ vs. } \tau, \xi \]

Figure 3. Tuning surfaces for PID control of the plants in the range $0 < \tau \leq 0.5$, $0 < \xi < 1$. 

Table 2. Tuning formula for PID control.

<table>
<thead>
<tr>
<th>$0 &lt; \tau \leq 0.5$</th>
<th>$0 &lt; \xi &lt; 1$</th>
<th>$0.5 &lt; \tau &lt; 1$</th>
<th>$0.4 \leq \xi &lt; 1$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$aK$</td>
<td>$T_i / L$</td>
<td>$T_d / L$</td>
<td>$b$</td>
</tr>
<tr>
<td>$a_0$</td>
<td>1.73</td>
<td>2.28</td>
<td>1.43</td>
</tr>
<tr>
<td>$a_1$</td>
<td>-17.51</td>
<td>0.87</td>
<td>-1.94</td>
</tr>
<tr>
<td>$a_2$</td>
<td>30.73</td>
<td>-24.00</td>
<td>14.82</td>
</tr>
<tr>
<td>$a_3$</td>
<td>-24.69</td>
<td>15.09</td>
<td>-21.44</td>
</tr>
<tr>
<td>$a_4$</td>
<td>0.15</td>
<td>-0.01</td>
<td>-0.25</td>
</tr>
<tr>
<td>$a_5$</td>
<td>-0.12</td>
<td>-0.02</td>
<td>0.16</td>
</tr>
<tr>
<td>$a_6$</td>
<td>3.30</td>
<td>-8.03</td>
<td>-1.06</td>
</tr>
<tr>
<td>$a_7$</td>
<td>33.07</td>
<td>45.21</td>
<td>-43.39</td>
</tr>
<tr>
<td>$a_8$</td>
<td>-37.64</td>
<td>-22.48</td>
<td>51.16</td>
</tr>
<tr>
<td>$a_9$</td>
<td>2.63</td>
<td>3.89</td>
<td>-3.25</td>
</tr>
<tr>
<td>$a_{10}$</td>
<td>-34.57</td>
<td>-22.39</td>
<td>36.04</td>
</tr>
<tr>
<td>$a_{11}$</td>
<td>36.88</td>
<td>8.32</td>
<td>-34.95</td>
</tr>
</tbody>
</table>

Figure 3. Tuning surfaces for PID control of the plants in the range $0 < \tau \leq 0.5$, $0 < \xi < 1$. 

Table 2. Tuning formula for PID control.
fitting two nonzero frequency points to a second-order plus dead time transfer function. In the following examples, Ho’s gain and phase margin method and Wang’s method use the same models.

**Example 1.** Consider a heavily oscillatory and short apparent dead time plant given by

\[ G(s) = \frac{15}{s^2 + 0.9s + 5(s + 3)}. \]

The plant model can be obtained through a step response experiment as

\[ G_p(s) = 5.009 e^{-0.2s} s^2 + 0.895s + 5.009. \]

Applying the proposed tuning method to this model, the controller parameters can be obtained as \( K = 0.916, T_i = 2.022, T_d = 0.562, \) and \( b = 0.36. \)

Wang’s frequency response fitting method gives the model

\[ e^{-0.246s} \frac{0.262s^2 + 0.228s + 1.243}{s}. \]

The parameters of the PID controller can be calculated using Wang’s method as follows:

\[ G_c(s) = 0.4631 + 2.5277s + 0.5337s. \]

The step and load disturbance responses of the controllers are given in Fig. 7(a). The proposed method produces better set point and load disturbance responses. The gain and phase margins of the system which was controlled by the controller designed using the proposed method are 77.7dB and 36.7°, respectively. Ho’s method cannot produce a proper controller for these gain and phase margin specifications.

For comparison purposes, the responses obtained using Ho’s method with GM = 2, PM = 30° and GM = 8, PM = 60° specifications are given in Fig. 7(b). The load disturbance response obtained using Ho’s method with GM = 2 and PM = 30° specifications is slightly better than...
that obtained using the proposed method, but the set point response is heavily oscillatory. The set point response obtained using Ho’s method with GM = 8, PM = 60° specifications is good, but the load disturbance response is sluggish.

Example 2. Consider the heavily oscillatory and high-order plant

\[ G(s) = \frac{18}{(s^2 + s + 2)(s + 3)^2}. \]

A step response experiment gives the model

\[ G_p(s) = \frac{1.52e^{-0.48s}}{s^2 + 0.9s + 1.52}. \]

The controller parameters obtained using the proposed method are \( K = 0.92 \), \( T_i = 1.075 \), \( T_d = 0.775 \), and \( b = 0.322 \). GM and PM for the system with this controller are 3.273 and 46.6°, respectively. Wang’s method produces the following model:

\[ \frac{e^{-0.531s}}{0.655s^2 + 0.613s + 1.157}. \]

The controller designed using Wang’s method is 0.223 + 0.422/s + 0.239s. For comparison with the proposed method, Ho’s method with GM = 3.273 and PM = 46.6° specifications was also applied to design the controller. The results are \( K = 0.783 \), \( T_i = 0.832 \), and \( T_d = 0.790 \).

The performance of each controller is shown in Fig. 8(a). Wang’s method has better set point response but the worst load disturbance response. Ho’s method with GM = 3.273 and PM = 46.6° specifications has the worst set point response. In fact, the actual GM and PM are 4.898 and 70°, respectively. The errors are about 50%.

Figure 8(b) shows the responses obtained using Ho’s method with GM = 2, PM = 30° and GM = 6, PM = 60° specifications. Ho’s method with GM = 2, PM = 30° specifications has slightly better load disturbance
response, but the set point response is heavily oscillatory. The set point response obtained using Ho’s method with GM = 6, PM = 60° specifications is good, but the load disturbance response is sluggish.

Example 3. Consider a high-order and moderately oscillatory plant given by

$$G(s) = \frac{3e^{-0.1s}}{(s^2 + 1.2s + 1)(s + 3)}.$$

A step response experiment gives the model

$$G_p(s) = \frac{1.075e^{-0.48s}}{s^2 + 1.273s + 1.075}.$$

The controller parameters obtained using the proposed method are $K = 1.801$, $T_i = 0.734$, $T_d = 0.568$ and $b = 0.232$. The system with this controller has GM = 7.943 and PM = 46°. The plant model obtained using Wang’s method is

$$\frac{e^{-0.351s}}{1.216s^2 + 1.267s + 1.092}.$$

Wang’s method produces the controller $0.466 + 0.402/s + 0.447s$. Ho’s method with GM = 7.943 and PM = 46° specifications produces the controller parameters $K = 0.941$, $T_i = 1.603$, and $T_d = 0.695$.

Figure 9(a) shows the responses of the system which has these controllers. Wang’s method has better set point response but the worst load disturbance response. Ho’s method with specifications GM = 7.943 and PM = 46° has set point response similar to that obtained using the proposed method but worse load disturbance response. The responses obtained using Ho’s method with GM = 2, PM = 30° and GM = 8, PM = 60° specifications are given in Fig. 9(b). Ho’s method with GM = 2 and PM = 30° specifications has good load disturbance response, but the set point response is heavily oscillatory. The set point response obtained using Ho’s method with GM = 8 and PM = 60° specifications is good, but the load disturbance response is sluggish.
Example 4. Consider a high-order and long apparent dead time plant given by

\[ G(s) = \frac{20e^{-2s}}{s^2 + 2.4s + 4}(s + 5). \]

A step response experiment gives the model

\[ G_p = \frac{4.386e^{-2.2s}}{s^2 + 2.513s + 4.386}. \]

The controller parameters obtained using the proposed method are \( K = 0.3729, \ T_i = 0.949, \ T_d = 0.294 \) and \( b = 0.329 \). The system with this controller has GM = 1.995 and PM = 52.2°. The plant model obtained using Wang’s method is

\[ e^{-2.165s} \]

\[ 0.257s^2 + 0.637s + 1.001. \]

Wang’s method produces the controller 0.147 + 0.231/s + 0.059s. Ho’s method with GM = 1.995 and PM = 52.2° specifications produces the controller parameters \( K = 0.235, \ T_i = 0.615, \) and \( T_d = 0.417 \).

Figure 10(a) shows the responses of these controllers. Wang’s method has better set point response. Ho’s method with GM = 1.995 and PM = 52.2° specifications has the worst set point and load disturbance responses. The actual GM and PM obtained using Ho’s method are 1.8621 and 41.5°, respectively. To compare Ho’s method with the proposed method further, we plot the responses obtained using Ho’s method with GM = 2, PM = 30° and GM = 3, PM = 60° specifications in Fig. 10(b). The actual GM and PM obtained using Ho’s method with GM = 2 and PM = 30° specifications are 2.239 and 50.5°, which are quite close to ours; hence, the responses are similar. The set point response obtained using Ho’s method with GM = 3 and PM = 60° specifications is better than that obtained using the proposed method.

Figure 11 shows the set point responses obtained using the proposed method with 50% error in \( b \). The variation in response is not so obvious. Thus, 50% error in \( b \) is acceptable when \( \tau \) is large.

In Wang’s method, the zeros of the PID controller are used to cancel out the poles of the plant model. Hence, the set point response is good, but the load disturbance response is sluggish as shown by the examples. Ho’s gain and phase method may have better set point or load disturbance responses than the proposed method if the gain and phase margins are specified properly. As shown in Example 2, the errors between the actual GM (PM) and the specified GM (PM) when Ho’s method is used...
may be large (more than 50%). The results of the examples also show that the proposed method provides a good balance between the set point and load disturbance responses.

**IV. CONCLUSIONS**

A new tuning formula for PID control of plants with under damped step responses has been given. The plants are modeled by means of second-order plus dead time transfer functions. This new formula is based on the dominant pole assignment method. Several examples have been given to show the effectiveness and robustness of this tuning formula.

**REFERENCES**


Jing-Chung Shen was born in Nantou, Taiwan in 1963. He received his B.S., M.S. and Ph. D. degree in National Cheng Kung University in 1985, 1987 and 1990 respectively, both in Electrical Engineering. From July 1990 to July 1992, he was an engineer in Computer and Communication Laboratory of Industrial Technology Research Institute, Hsinchu, Taiwan. Since August 1992, he joined the Department of Automation Engineering, National Huwei Institute of Technology. Currently, he is an Associate Professor. His research interests include robust control, intelligent control and application of Digital Signal Processors.