PID Controller Based Intelligent Fuzzy Control of a SPM System Design
JIUM-MING LIN and PO-KUANG CHANG
Ph.D. Program in Engineering Science, College of Engineering
Chung-Hua University
707, Sec. 2 Wu-Fu Rd. Hsin-Chu, 30012.
TAIWAN, R. O. C.
jmlin@chu.edu.tw    http://www.cm.chu.edu.tw/chinese/teacher/MING/index.htm

Abstract: - This research is to use Ziegler-Nichols PID controller as a basement for the fuzzy controller design in a Scanning Probe Microscope (SPM) to reduce the hysteresis effect. Comparing the results with a previous design for the outer-loop with PI compensator are also made, one can see that the proposed system is more robust.

Key-Words: - Ziegler-Nichols PID controller, PID Fuzzy controller, SPM, Hysteresis effect, LVT

1 Introduction
The SPM has been developed rapidly in last three decade [1]–[10]. Its usage is very extensive, e. g. the measurements of physical distribution and material property such as surface profile, roughness, static charge, magnetic dipole, friction, elasticity, and thermal conductivity. As the block diagrams in Fig. 1 of a previous research [11], a balance with stylus probe, force actuator, LVDT, load cell, personal computer, and XYZ-stages were integrated into a contact force-controlled SPM, such that the surface of the sample would not be destroyed by the stylus probe. To reduce the hysteresis effect of the force actuator this research in Fig. 2 applied a Ziegler-Nichols PID controller as a basement for the fuzzy controller design [12-14] in the outer-loop and LVT in the feedback loop of a SPM.

The organization of this paper is as follows: the first section is introduction. The second and the third ones are respectively for the review of previous research and the proposed fuzzy controller design. The last part is the conclusion.

2 Review of Previous System Design
The force actuator is consisted of a coil and a spring. As in Fig. 3(a) the rod returns to the initial place when the force actuator de-energized. On the other hand, if a voltage is applied across the coil, then there is current in the coil, and a force is generated to compress the spring and make the rod pull down as in Fig. 3(b). The relationship of the applied voltage and displacement is shown in Fig. 3(c). To reduce the hysteresis effect this research is to use a fuzzy controller to replace the PI compensator for a previous research, the newly system model is shown in Fig.2. Table I listed the previous PI compensators [11] for inner and outer loops design (steady state errors are equal to zero for inner and outer loops) in Fig 1. In addition, the gain margins, phase margins of the inner (GM1, PM1) and outer (GM2, PM2) loops as well as the phase crossover frequency ωc are also included.

The outputs of LVDT for saw tooth shaped input (as in Fig.4) of cases 1, 2, 5 and 6, are respectively shown from Figs. 5 to 8 for comparison (hysteresis effect parameter H=0.3). One can see that the larger the outer-loop phase margin, the lower the hysteresis effect, but all the hysteresis effects are still very dominant. Because ωc are very large for these cases, then the time and phase delays would be increased by the hysteresis effect. Thus the stability can even be degraded by adding the hysteresis effect to push the resulting phase margins be zero.

3 Ziegler-Nichols PID Controller Design
Ziegler and Nichols had proposed two famous PID controller design methods [14], which can be applied for a linear control system design. The details are briefed as follows.

3.1 Ziegler-Nichols PID Controller Design (Method 1)
The first one is applied for a system without having the transfer function in advance, one can make the unit-step input response as shown in Fig.9, from which we can determine the gain K of the steady-state response, the time constant T, the time delay L, as
well as the y-intercept \( a \) of the intersect point and the output axis for the case of maximum slope. Then one has the plant transfer function as follows:

\[
G(s) = \frac{Ke^{-Ls}}{Ts + 1}
\]  

The first PID coefficients selection rule is as listed in Table II, in which \( K_P, T_I \) and \( T_D \) are respectively the gain of PID controller coefficients and are related to the magnitudes of \( a \) and \( L \). The abbreviation NA stands for not available.

Applying a unit step input to the previous system with PI compensator [11] for inner loop design (steady state error is equal to zero) in Fig 1, the unit step response is in Fig. 10. One can find that \( K=1, L=0.3, T=0.9 \) and \( a=0.25 \). By Table II one has the gains of PID compensator (1) as: \( P=4.8, I=0.6 \) and \( D=0.15 \). The response of the system with PID compensator (1) is in Fig. 11. One can see the performance of the result is better than those of the previous ones as in Fig. 5-8 with \( H=0.3 \).

Fig. 1 Block diagram of SPM with PI compensator for outer-loop feedback in the previous research [11].

Fig. 2 Block diagram of SPM with a fuzzy controller in the outer-loop of this research.

Fig. 3 Actuator (a) de-energized, (b) energized states, and (c) applied voltage vs. displacement.
Table I Previous design results of system in Fig. 1.

<table>
<thead>
<tr>
<th>Case</th>
<th>K1</th>
<th>K2</th>
<th>K3</th>
<th>K4</th>
<th>GM1</th>
<th>PM1 (Deg)</th>
<th>GM2</th>
<th>PM2 (Deg)</th>
<th>$\omega_c$ (r/sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>12</td>
<td>120</td>
<td>1</td>
<td>200</td>
<td>$\infty$</td>
<td>73</td>
<td>$\infty$</td>
<td>85</td>
<td>9840</td>
</tr>
<tr>
<td>2</td>
<td>10</td>
<td>100</td>
<td>0.8</td>
<td>180</td>
<td>$\infty$</td>
<td>75</td>
<td>$\infty$</td>
<td>70</td>
<td>7500</td>
</tr>
<tr>
<td>3</td>
<td>15</td>
<td>100</td>
<td>1.5</td>
<td>200</td>
<td>$\infty$</td>
<td>65</td>
<td>$\infty$</td>
<td>88</td>
<td>20000</td>
</tr>
<tr>
<td>4</td>
<td>20</td>
<td>150</td>
<td>2</td>
<td>150</td>
<td>$\infty$</td>
<td>63</td>
<td>$\infty$</td>
<td>89.5</td>
<td>40000</td>
</tr>
<tr>
<td>5</td>
<td>8</td>
<td>80</td>
<td>0.5</td>
<td>300</td>
<td>$\infty$</td>
<td>85</td>
<td>$\infty$</td>
<td>60</td>
<td>30000</td>
</tr>
<tr>
<td>6</td>
<td>18</td>
<td>200</td>
<td>1.3</td>
<td>220</td>
<td>$\infty$</td>
<td>70</td>
<td>$\infty$</td>
<td>90</td>
<td>30000</td>
</tr>
</tbody>
</table>

Fig. 4 A saw tooth shaped command as input.  
Fig. 7 Previous design output of case 5 in Fig. 1 (H= 0.3).

Fig.5 Previous design output of case 1 in Fig.1 (H=0.3).  
Fig.8 Previous design output of case 6 in Fig.1 (H= 0.3).

Fig.6 Previous design output of case 2 in Fig.1 (H=0.3).  
Fig.9 The unit-step input response of a system.

Fig.10 The unit-step input response of a SPM system.  
Fig.11 The response with PID compensator (1) (H=0.3).
### Table II The second PID coefficients selection rule.

<table>
<thead>
<tr>
<th>Controller Type</th>
<th>$K_p$</th>
<th>$T_I$</th>
<th>$T_D$</th>
</tr>
</thead>
<tbody>
<tr>
<td>P</td>
<td>$1/a$</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>PI</td>
<td>$0.9/a$</td>
<td>$3L$</td>
<td>NA</td>
</tr>
<tr>
<td>PID</td>
<td>$1.2/a$</td>
<td>$2L$</td>
<td>$L/2$</td>
</tr>
</tbody>
</table>

### 3.2 Ziegler-Nichols PID Controller Design (Method 2)

This case is used for a system with a predetermined transfer function. Thus one can get gain margin (GM) and phase-crossover frequency $\omega$ from the Bode plot as in Fig. 12. Then one can obtain $K_u$ and $T_u$ as:

$$K_u = \log\left(\frac{1}{1-\frac{GM}{20}}\right) = 10^{\frac{GM}{20}}$$ (2)

and

$$T_u = \frac{2\pi}{\omega}$$ (3)

### Table III The second PID coefficients selection rule.

<table>
<thead>
<tr>
<th>Controller Type</th>
<th>$K_p$</th>
<th>$T_I$</th>
<th>$T_D$</th>
</tr>
</thead>
<tbody>
<tr>
<td>P</td>
<td>$0.5K_u$</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>PI</td>
<td>$0.45K_u$</td>
<td>$0.83T_u$</td>
<td>NA</td>
</tr>
<tr>
<td>PID</td>
<td>$0.6K_u$</td>
<td>$0.5T_u$</td>
<td>$0.125T_u$</td>
</tr>
</tbody>
</table>

The next step is to make the Bode plot, the result is as in Fig. 13. Thus one has GM=16.9dB and $\omega = 7.7$ rad/sec (phase-crossover frequency). The third step is to apply (2) and (3) to obtain $K_u=7,$ and $T_u=0.816$. By Table III one has the gains of PID compensator (2) as: $P=4.2, I=0.408$ and $D=0.102$. The response with PID compensator (2) is in Fig. 14. One can see the performance of the result is better than those of the previous ones [11] as in Figs.5-8 with H= 0.3.

### 4 Fuzzy Controller Design

This section will directly apply the Ziegler-Nichols PID controller design results (Methods 1 and 2) obtained in Section III for the fuzzy PID controller design. The fuzzy PID controller as shown in Fig.15 combines both an integrator and a fuzzy PD controller. It is well-known that fuzzy controller is based on the IF-THEN RULE as follows:

![Fig. 13 The gain margin (GM) and phase-crossover frequency $\omega$ of a SPM system.](image)

![Fig. 14 Response with PID compensator (2) (H= 0.3).](image)

![Fig. 15 The fuzzy PID controller is obtained by applying an integrator and a fuzzy PD controller.](image)
R1: IF E is NB AND \(\Delta E\) is NB THEN U is NB,
R2: IF E is NB AND \(\Delta E\) is ZE THEN U is NM,
R3: IF E is NB AND \(\Delta E\) is PB THEN U is ZE,
R4: IF E is ZE AND \(\Delta E\) is NB THEN U is NM,
R5: IF E is ZE AND \(\Delta E\) is ZE THEN U is ZE,
R6: IF E is ZE AND \(\Delta E\) is PB THEN U is PM,
R7: IF E is PB AND \(\Delta E\) is NB THEN U is ZE,
R8: IF E is PB AND \(\Delta E\) is ZE THEN U is PM,
R9: IF E is PB AND \(\Delta E\) is PB THEN U is PB,

where NB, NM, NS, ZE, PS, PM, and PB respectively stand for negative big, negative middle, negative small, zero, positive small, positive middle and positive big. The detailed cross reference rules for the inputs and output of fuzzy controller are defined in Table IV. According to fuzzy control design method the membership function parameters

of error E, \(\Delta E\) (deviations of present E and the previous E), and U (control input) are defined at first, and listed in Table V. To reduce the computation time the triangular distribution functions are applied in fuzzy controller relationship functions calculation instead of using the traditional Gaussian ones.

Table IV. The detailed cross reference rules for the inputs and output of the fuzzy PD controller.

<table>
<thead>
<tr>
<th>E/(\Delta E)</th>
<th>NB</th>
<th>NM</th>
<th>NS</th>
<th>ZE</th>
<th>PS</th>
<th>PM</th>
<th>PB</th>
</tr>
</thead>
<tbody>
<tr>
<td>NB</td>
<td>NB</td>
<td>NB</td>
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<td>NS</td>
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<td>ZE</td>
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<td>NS</td>
<td>ZE</td>
<td>PS</td>
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<tr>
<td>NS</td>
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<td>NS</td>
<td>NS</td>
<td>ZE</td>
<td>PS</td>
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<td>PM</td>
</tr>
<tr>
<td>ZE</td>
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<td>PS</td>
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<td>PM</td>
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<tr>
<td>PS</td>
<td>PM</td>
<td>ZE</td>
<td>PS</td>
<td>PS</td>
<td>PM</td>
<td>PM</td>
<td>PB</td>
</tr>
</tbody>
</table>

Table V. Fuzzy PD controller cross reference rules.

<table>
<thead>
<tr>
<th>Item</th>
<th>Parameter E</th>
<th>Parameter (\Delta E)</th>
<th>Parameter U</th>
</tr>
</thead>
<tbody>
<tr>
<td>Negative Big (NB)</td>
<td>[-1 -1 -0.75 -0.3]</td>
<td>[-4.5 -4.5 -3.375 -1.35]</td>
<td>[-12 -12 -9.6 -8.4]</td>
</tr>
<tr>
<td>Negative Medium (NM)</td>
<td>[-0.75 -0.3 -0.15]</td>
<td>[-3.375 -1.35 -0.72]</td>
<td>[-9.6 -8.4 -7.2]</td>
</tr>
<tr>
<td>Negative Small (NS)</td>
<td>[-0.15 -0.1 0]</td>
<td>[-1 -0.5 0]</td>
<td>[-8.4 -4.8 0]</td>
</tr>
<tr>
<td>Zero (ZE)</td>
<td>[-0.05 0 0.05]</td>
<td>[-0.25 0.25]</td>
<td>[-4.8 0.48]</td>
</tr>
<tr>
<td>Positive Small (PS)</td>
<td>[0.1 0.15]</td>
<td>[0.5 1]</td>
<td>[0.4 8.4]</td>
</tr>
<tr>
<td>Positive Medium (PM)</td>
<td>[0.15 0.3 0.75]</td>
<td>[0.72 1.35 3.375]</td>
<td>[7.2 8.4 9.6]</td>
</tr>
<tr>
<td>Positive Big (PB)</td>
<td>[0.3 0.75 1 1]</td>
<td>[1.35 3.375 4.5 4.5]</td>
<td>[8.4 9.6 12 12]</td>
</tr>
</tbody>
</table>

4.1 Fuzzy Controller Design Based on Ziegler-Nichols PID Controller Design (Method 1)

Fig. 16 shows the system response with fuzzy PID controller (1) (H=0.3). In addition, the XY-plot of input and output is as in Fig.17. The hysteresis effect is almost disappeared, so that this method is better than those obtained by the previous PI controllers [11] as well as the one with PID in Section 3.

Fig. 17 The XY-plot of input and output for fuzzy controller (1) (H=0.3).

4.2 Fuzzy Controller Design Based on Ziegler-Nichols PID Controller Design (Method 2)

Fig. 18 shows the response of the system with fuzzy PID controller (2) (H=0.3). In addition, the XY-plot of input and output is as in Fig.19. It can be seen that the hysteresis effect is almost disappeared, so that this method is better than those obtained by the
previous PI controllers [11] as well as the one with PID in Section 3.

![Fig. 18 The output with fuzzy PID controller (2) (H=0.3).](image1)

![Fig. 19 The XY-plot of input and output for fuzzy controller (2) (H=0.3).](image2)

### [6] Conclusion

This research applied fuzzy control method for a Scanning Probe Microscope (SPM) system design. In addition, the actuator hysteresis effect was taken into consideration. Comparing the proposed method with a previous work are also made, it can be seen that the results of system performance obtained by the fuzzy PID controller (1) is much better.

#### Acknowledgment

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#### References:


