Contact Force-Controlled SPM System Design with Fuzzy Controller

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Abstract: - This research applied both the traditional PI (Proportion and Integration) compensator and the PD (Proportion and Derivation) type fuzzy controller for a ccontact force-controlled Scanning Probe Microscope (SPM) system design. In addition, the actuator hysteresis effect was taken into consideration. It can be seen that the system performance obtained by the proposed fuzzy controller was much better, especially in eliminating the actuator hysteresis effect. This improvement has been verified by MATLAB simulation and practical implementation of a surface profiler.

Key-Words: - Scanning probe microscope, Force actuator, Hysteresis effect, Fuzzy controller

1 Introduction

The Scanning Probe Microscopy (SPM) has been developed rapidly in the last two decade [1-10]. Its usage is very extensive, for example, the measure-ments of physical distribution and material property such as surface profile, rough-ness, static charge, magnetic dipole, friction, elasticity, and thermal conductivity. As shown in Fig.1 of previous research [11], a balance with stylus probe, force actuator, LVDT (Linear Variable Differential Trans-former), load cell, personal computer, and XYZ-stages was integrated into a contact-force-controlled Scanning Probe Microscope (SPM) system, such that the surface of the sample would not be destroyed by the contact force produced by the stylus probe. This research is to use Linear Velocity Transducer (LVT) in Fig.2 to detect the vertical velocity of the stylus probe for the inner-loop damping and transient control of the force actuator. The stylus probe is shown in Fig.3, the voice coil was applied as a force actuator (Fig.4), which was integrated with LVT and LVDT (Fig.5) to measure probe vertical displacement and velocity. The load cell in Fig.6 was to detect the contact force between the probe and sample to be tested.

A leaf spring was applied to integrate the load cell with voice coil, LVT and LVDT into a probe module as shown in Figs.7-8. In addition to the XYZ-stages a piezo-stage in Fig.9 was also put on the Z-stage to improve the measurement accuracy. The personal computer was the central control unit for the whole operation, such as setting the contact force between the probe and the sample, taking the contact force information from the load cell, as well as driving the force actuator for the balance-arm initial leveling. Thus it is an automatic SPM system.

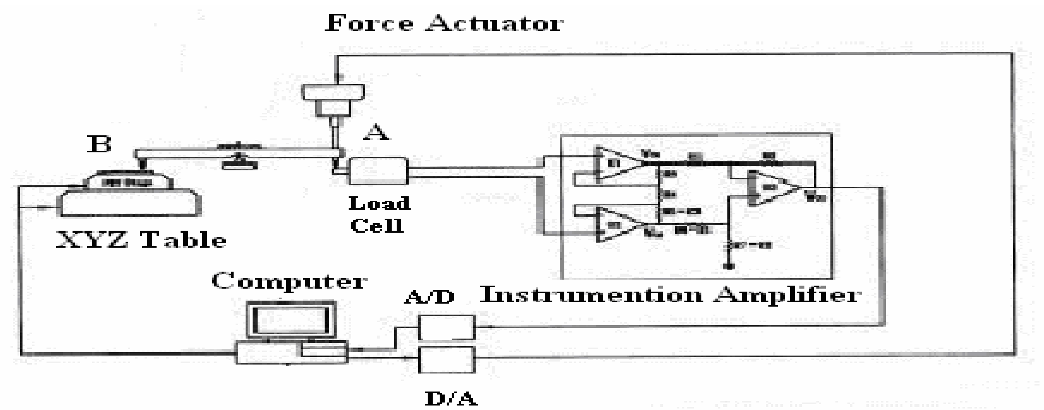


Fig.1 The contact force-controlled SPM system.

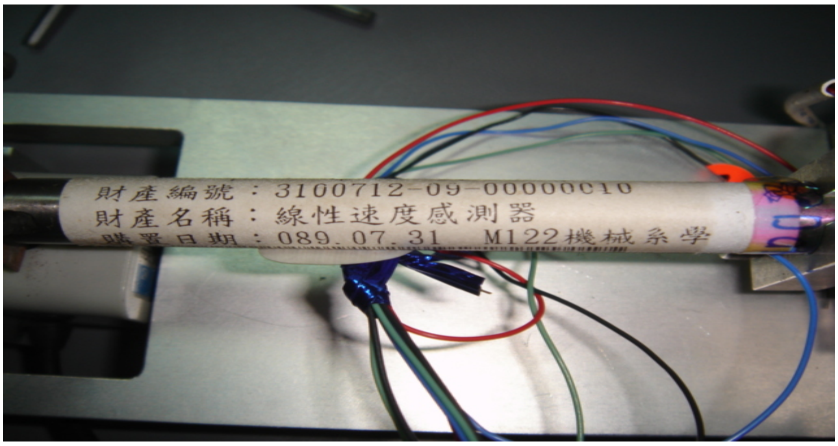


Fig.2 The LVT is to detect probe vertical velocity.

Fig.3 Stylus probe.

Fig.4 Voice coil.

Fig.5 LVDT.

Fig.6 Load cell.

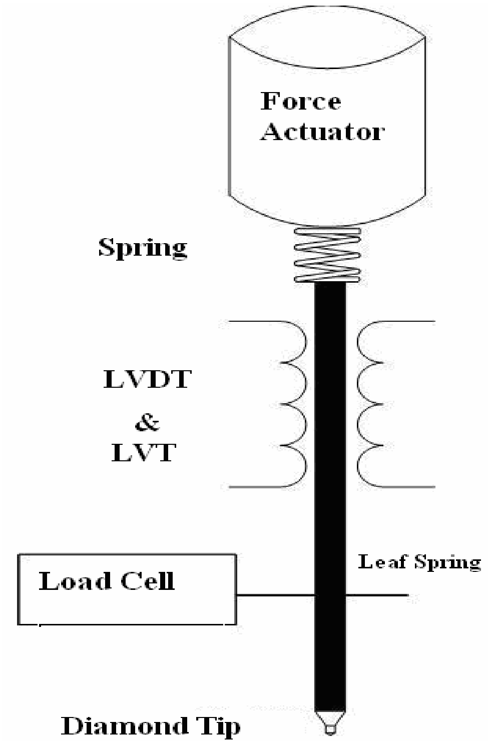


Fig.7 The installation method of probe module.

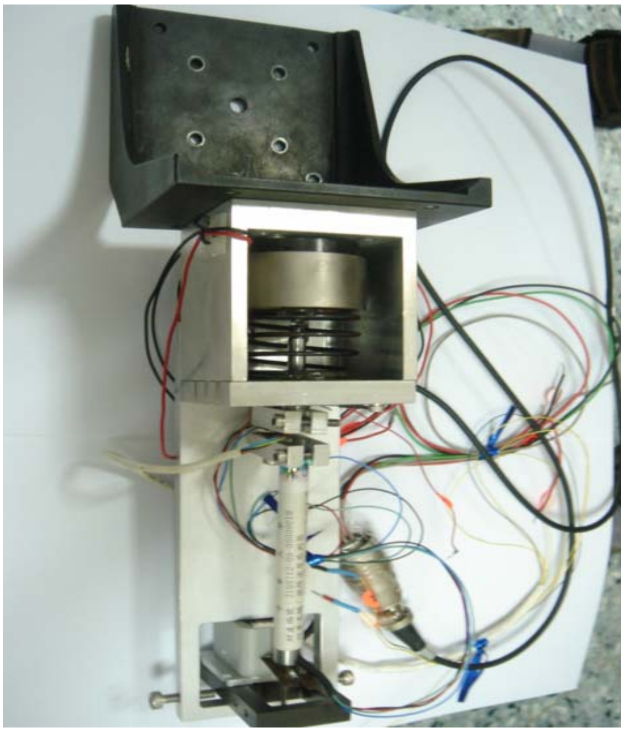


Fig.8 The picture of probe module.

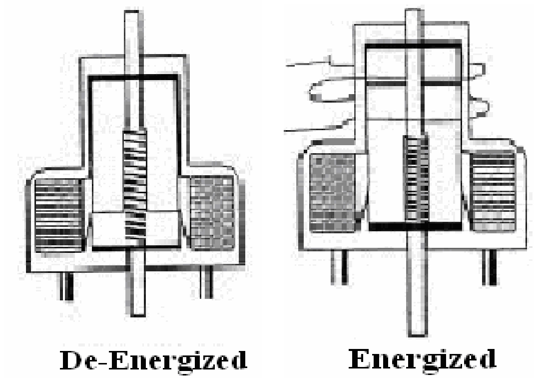
Firstly, this research applied the PI compensator or fuzzy controller [14-18] for the SPM control system design. In addition, the actuator hysteresis effect was taken into consideration. For comparison purpose the system by integrating both controllers was also applied, it can be seen that the system performance obtained by the integration controller was much better, especially in eliminating the actuator hysteresis effect. This improvement has been verified by MATLAB simulation and practical implementation of a surface profiler.design.

Fig.9 The piezo-stage and the sample holder.

The organization of this paper is as follows: the first section is introduction. The second one is for traditional PI compensator design. The fuzzy control method is given in Section 3. The system design by integrating both controllers was applied in Section 4. The last part is the conclusion.

2 PI Control System Design

The structure of the system is shown in Fig.1. The major part is the balance. The stylus probe is on the left side, while the force actuator and the load cell are on the upper and the lower parts of the right side, respectively. The force actuator is consisted of a coil and a spring, as in Fig.10a the rod returns to the initial place when the force actuator de-energized, when 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 shown in Fig. 10b. The relationship of the applied voltage and the displacement is shown in Fig.11. In order to reduce the hysteresis-effect of the force actuator in Fig.11, a PI compensator in the forward path as well as a LVT measuring the vertical velocity as the feedback path of the force actuator, were applied in this research as shown in Fig.12.



(a) (b)

Fig.10 Actuator (a) De-energized. (b) Energized.

The first step of test is initial levelling of the balance lever arm, which is achieved by adjusting the current through the coil of force actuator. Since the lever arm weight at the stylus probe (contact with the sample) side is heavier than the other side (contact with actuator) intentionally, thus the force actuator should push down to make the balance lever arm even. The contact point of the lever arm on the load cell is installed right at the calibrated-levelling height. This adjustment process stops when the value of load cell output increases from 0 mg to 40 mg as shown in Fig. 13. This value for the weight discrimination can be lowered if the circuit routing condition is better, thus the noise amplitude at the load cell output can be reduced.

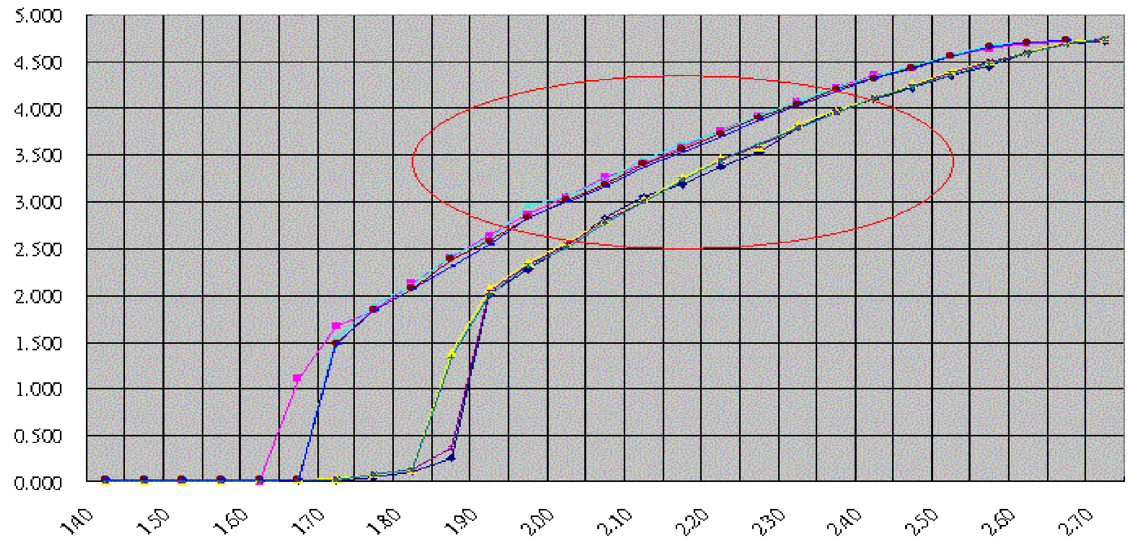


Fig.11 Actuator applied voltage vs. displacement.

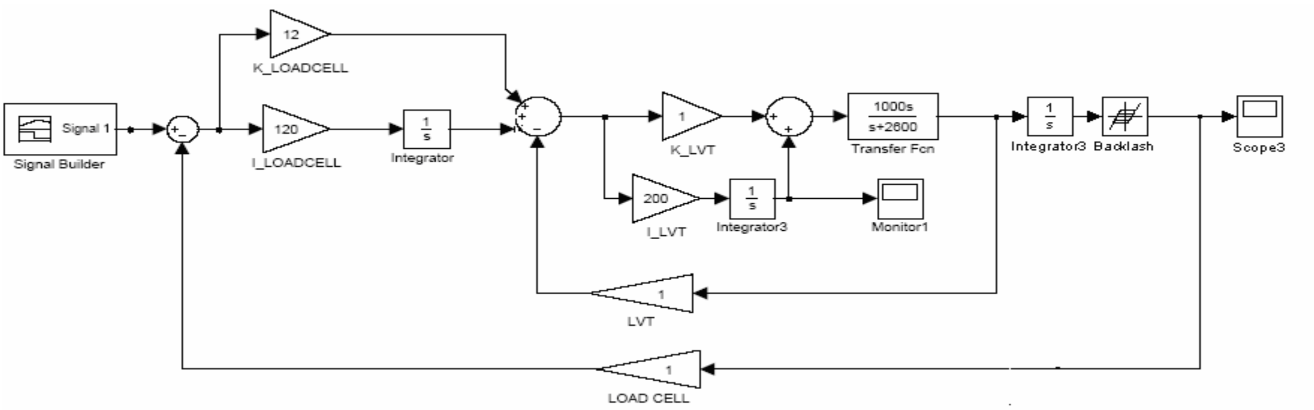


Fig.12 The design with a PI compensator and a LVT respectively in the forward and feedback paths of actuator.

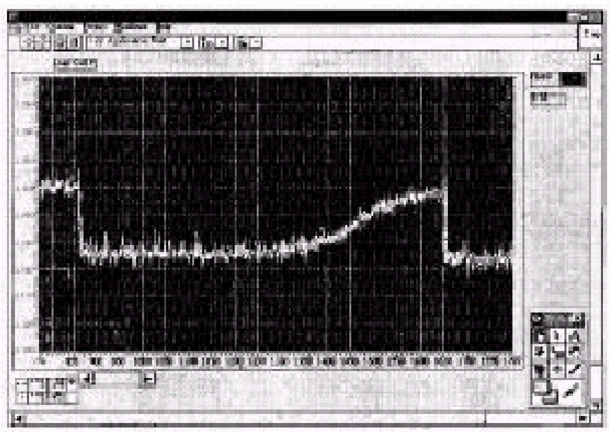


Fig.13 Output voltage of load cell is increased for contact force changing from 0 mg to 40 mg.

The next step is to load the sample on the holder which is fixed on the piezo-stage as well as XYZ-stages, and then setting the XY-stages (the resolution is 34 nm in either axis) to make the first sampled point just right under the tip of the stylus probe, then raising the piezo-stage upward until the sampled point touching with the probe. The value of the probe contact force on the sample can be obtained by the load cell. To avoid destroying the sample, the maximum contact force is limited to 100 mg, i.e. if the contact forces magnitude is smaller than 100 mg, then moving the piezo-stage upward by one step (the resolution is 10 nm), otherwise, stop. By scanning the XY-stages in either x- or y-axis, then the surface profile of sample can be obtained from LVDT. After a little while of trial-and-error one has the result with P=1 and I=200, respectively, e.g. the output of force actuator with the backlash parameter [15] D to be as 0.1 and 0.3 by using a triangular input are shown in Figs.14-15, respectively. It can be seen that the nonlinear hysteresis effect is dominant. Finally, the simulation block diagram of the whole system is shown in Fig.13, in which the desired contact force between the probe and the sample is set as the input command to the system, and a load cell is used as the outer feedback loop sensor.

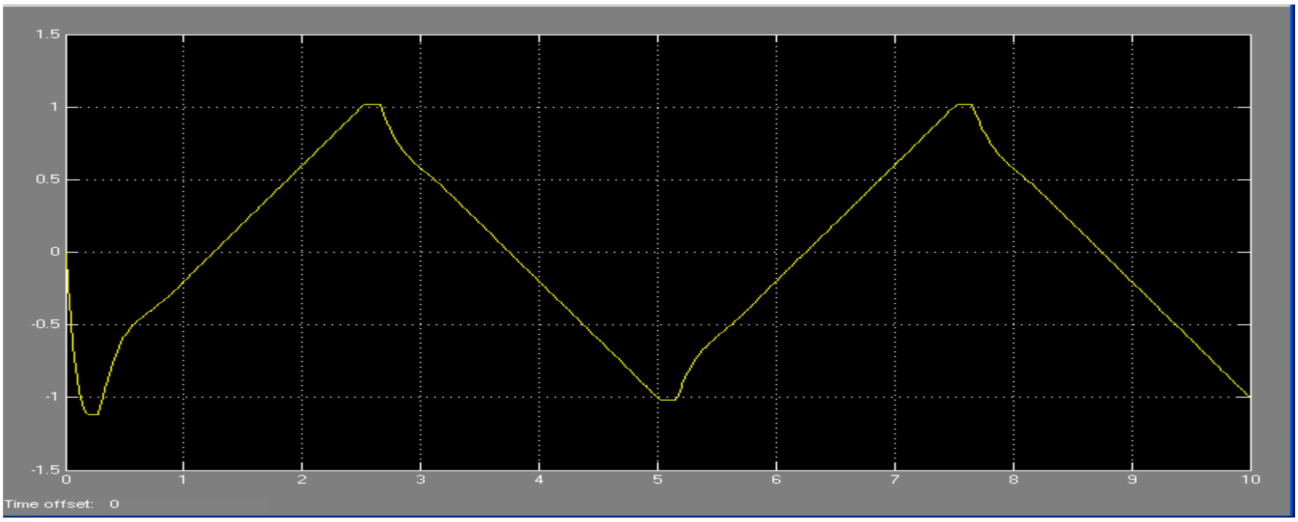


Fig.14 Output of LVDT for D=0.1 with P=1 and I=200.

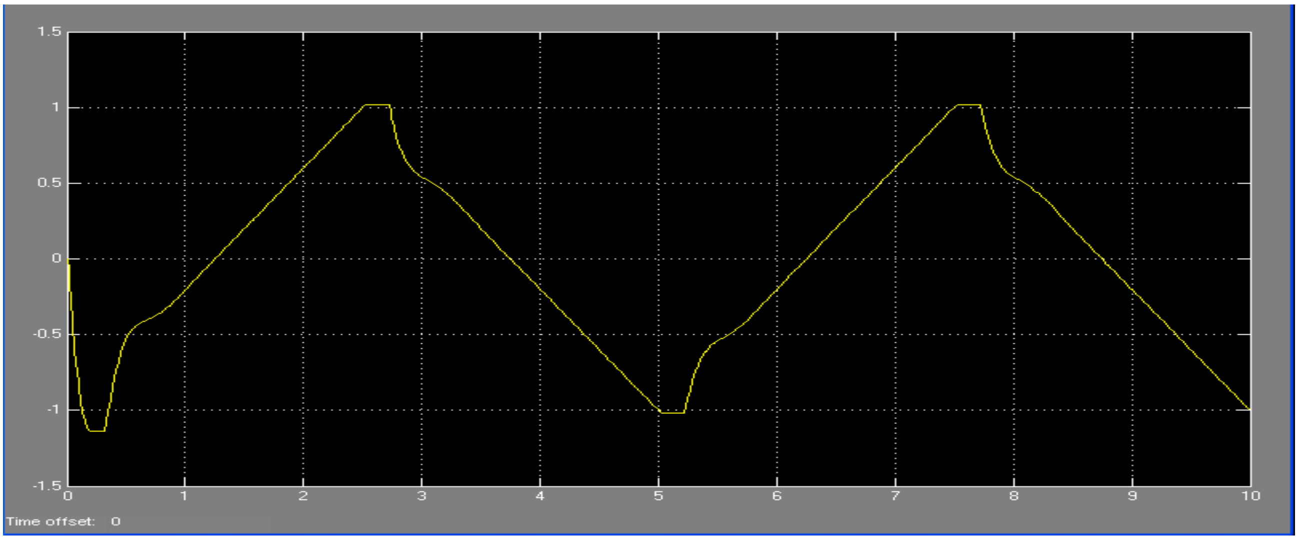


Fig.15 output of LVDT for D=0.3 with P=1 and I=200.

3 Fuzzy Control System Design

In this section a Proportion and Derivative (PD) type fuzzy control design method [13-15] is applied for the system design. It is well-known that the fuzzy controller is based on the following IF-THEN RULE, e. g.

R1：IF E is NB AND ΔE is NB THEN U is NB,
R2：IF E is NB AND ΔE is ZE THEN U is NM,
R3：IF E is NB AND ΔE is PB THEN U is ZE,
R4：IF E is ZE AND ΔE is NB THEN U is NM,
R5：IF E is ZE AND ΔE is ZE THEN U is ZE,
R6：IF E is ZE AND ΔE is PB THEN U is PM,
R7：IF E is PB AND ΔE is NB THEN U is ZE,
R8：IF E is PB AND ΔE is ZE THEN U is PM,
R9：IF E is PB AND ΔE is PB THEN U is PB,

where E is the error of the contact force, and ΔE is the deviation of present E and the previous E. In addition, 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 system fulfills the following equations (1) and (2):

$$U(k) = f(E(k), \Delta E(k)) \quad (1)$$
$$U(k) = k_P E(k) + k_D \Delta E(k) \quad (2)$$

The detailed cross reference rules for the inputs and output of fuzzy controller are defined in Table 1. According to the fuzzy control design method the relationship functions of E, ΔE and U (Control Input) are defined at first, which are listed in Tables 2-4 and shown in Figs. 16-18. The MATLAB simulation block diagram of the whole system with the proposed fuzzy controller is shown in Fig. 19. Then the performance design by the proposed fuzzy controller is analyzed by simulation. Figs. 20-21 show the responses for the backlash to be as 0.1 and 0.3, respectively. It can be seen that the results are better than those obtained by the traditional PI controller.

Table 1 Fuzzy controller cross reference rules.

E /Δ*E*	NB	NM	NS	ZE	PS	PM	PB
NB	NB	NB	NM	NM	NS	NS	ZE
NM	NB	NM	NM	NS	NS	ZE	PS
NS	NM	NM	NS	NS	ZE	PS	PS
ZE	NM	NS	NS	ZE	PS	PS	PM
PS	NS	NS	ZE	PS	PS	PM	PM
PM	NS	ZE	PS	PS	PM	PM	PB
PB	ZE	PS	PS	PM	PM	PB	PB

Table 2 The relationship functions of *E*.

Item	Type	Parameter
Negative Big (NB)	Trapmf	[-1 -1 -0.75 -0.3]
Negative Medium (NM)	Trimf	[-0.75 -0.3 -0.15]
Negative Small (NS)	Trimf	[-0.15 -0.1 0]
Zero (ZE)	Trimf	[-0.05 0 0.05]
Positive Big(PB)	Trimf	[0 0.1 0.15]
Positive Medium (PM)	Trimf	[0.15 0.3 0.75]
Positive Small(PS)	Trapmf	[0.3 0.75 1 1]

Table 3 The relationship functions of Δ*E*.

Item	Type	Parameter
Negative Big (NB)	Trapmf	[-4.5 -4.5 -3.375 -1.35]
Negative Medium (NM)	Trimf	[-3.375 -1.35 -0.72]
Negative Small (NS)	Trimf	[-1 -0.5 0]
Zero (ZE)	Trimf	[-0.25 0 0.25]
Positive Big(PB)	Trimf	[0 0.5 1]
Positive Medium (PM)	Trimf	[0.72 1.35 3.375]
Positive Small(PS)	Trapmf	[1.35 3.375 4.54.5]

Table 4 The relationship functions of *U*.

Item	Type	Parameter
Negative Big (NB)	Trapmf	[-12 -12 -9.6 -8.4]
Negative Medium (NM)	Trimf	[-9.4 -8.6 -7.2]
Negative Small (NS)	Trimf	[-8.4 -4.8 0]
Zero (ZE)	Trimf	[-4.8 0 4.8]
Positive Big(PB)	Trimf	[0 4.8 8.4]
Positive Medium (PM)	Trimf	[7.2 8.4 9.6]
Positive Small(PS)	Trapmf	[8.4 9.6 12.12]

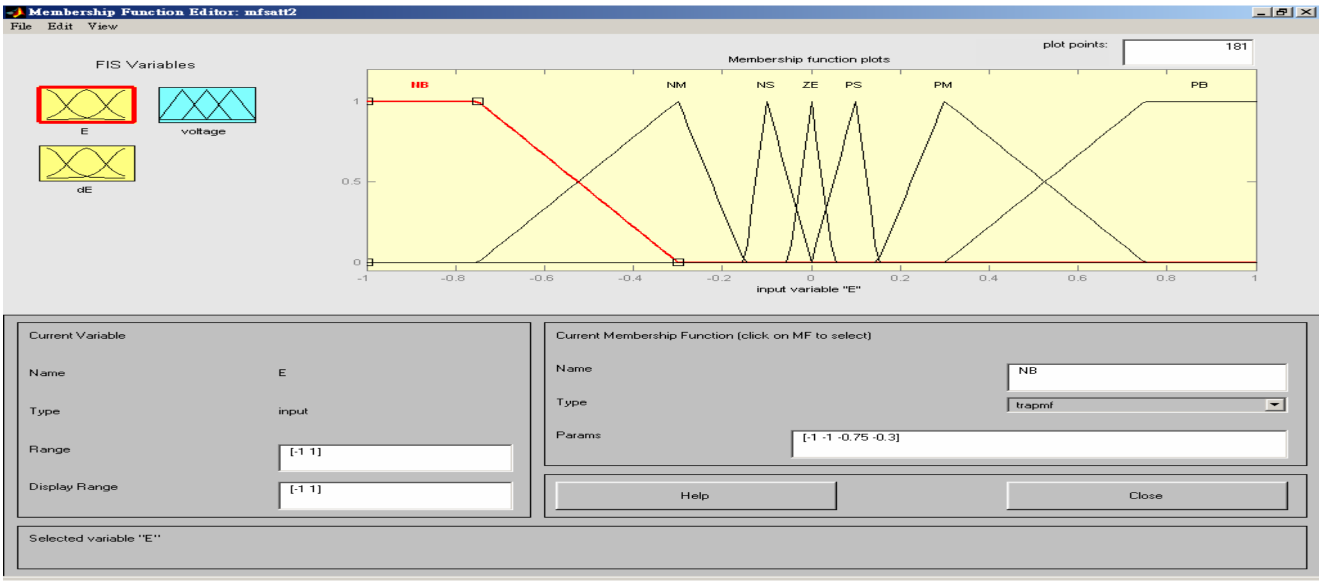


Fig. 16 The relationship functions of Δ*E*.

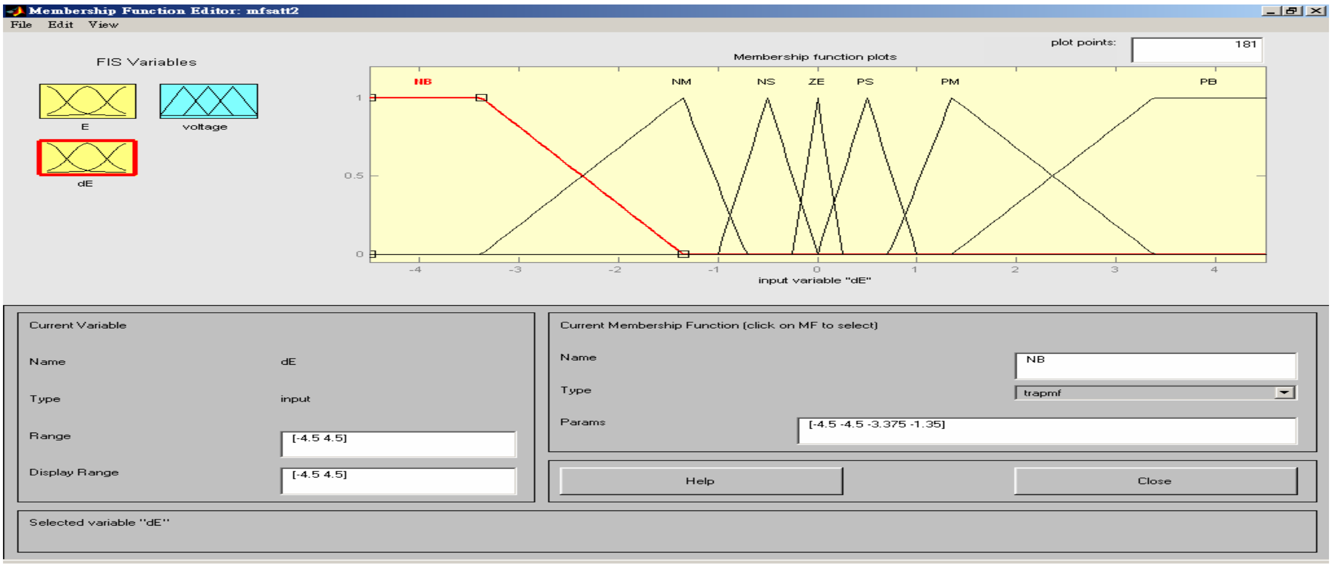


Fig. 17 The relationship functions of *E*.

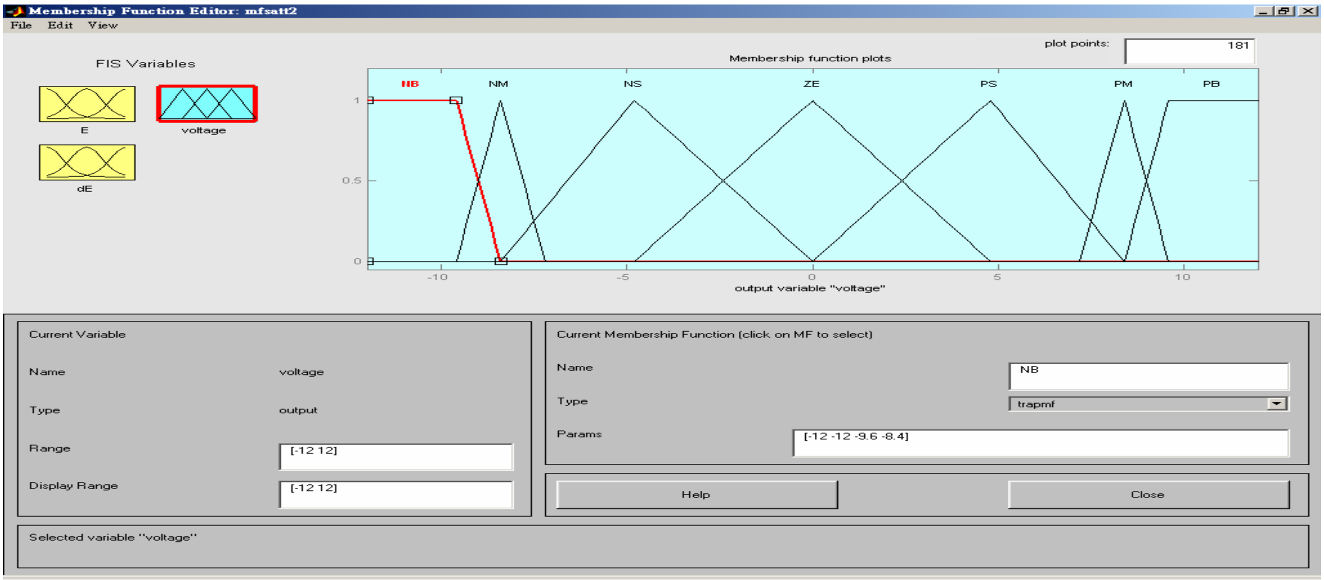


Fig. 18 The relationship functions of *U*.

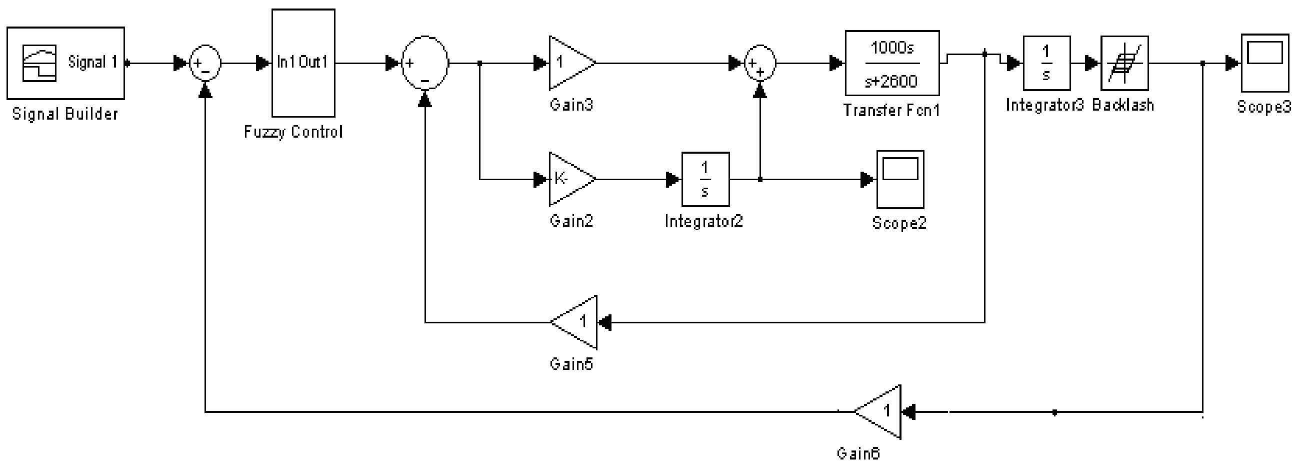


Fig.19 The proposed SPM system design with a Fuzzy controller.

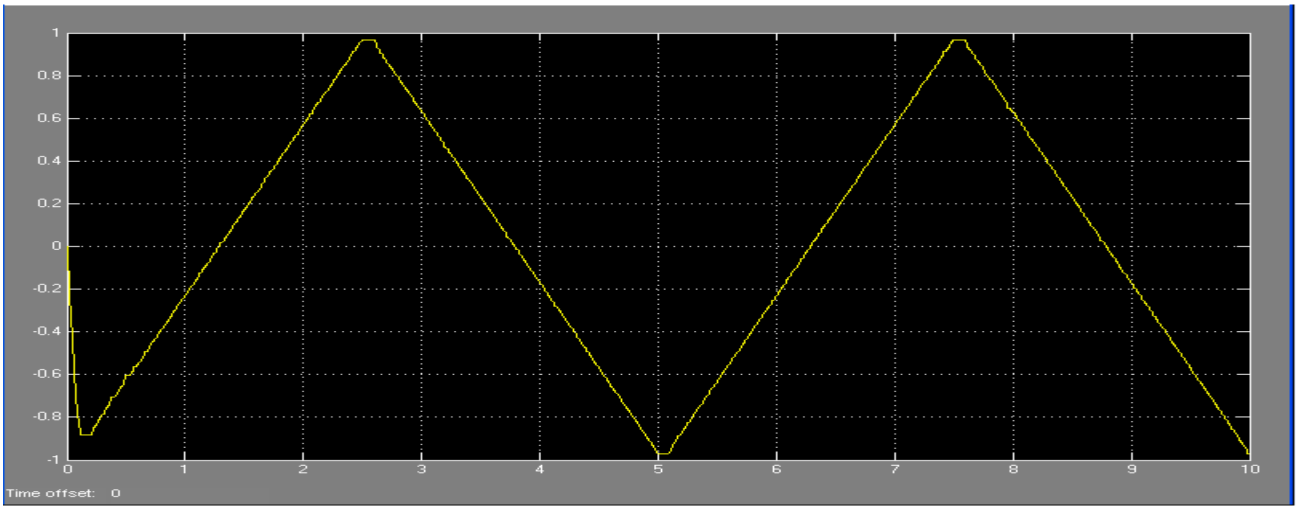


Fig. 20 Output with the proposed fuzzy control for D=0.1.

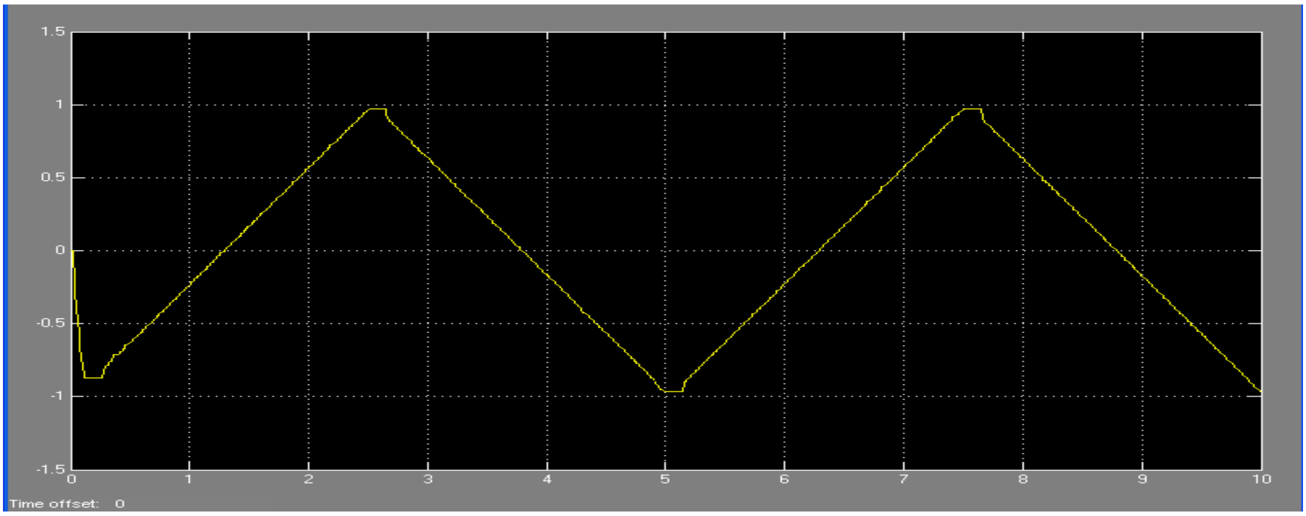


Fig. 21 Output with the proposed fuzzy control for D=0.3.

4 Test Results and Discussions

After demonstrating the operation principle of the proposed SPM system, a sample was applied for performance evaluation. It is a substrate of Ball Grid Array (BGA) package, by applying the proposed SPM system is shown in Fig.22. For comparison purpose a commercial ET-4000 was also applied, the surface profile of which was shown in Fig. 23. Thus one can see that the performance of the proposed system was very good.

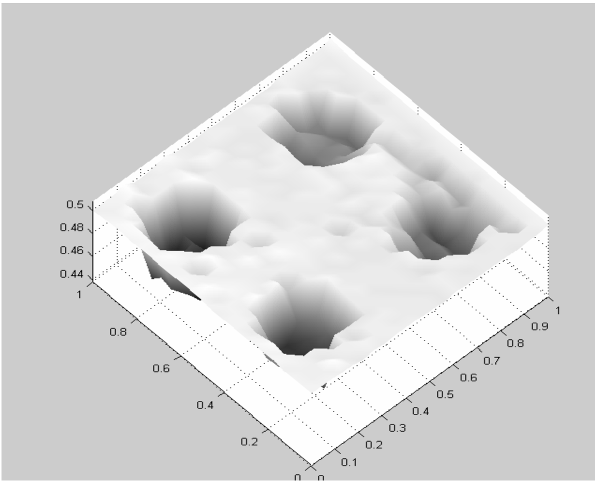


Fig.22 The surface profile of a BGA substrate with the proposed SPM system with fuzzy controller.

5 Conclusion

This paper integrates the mechatronics such as: a balance with stylus probe, force actuator, LVT, LVDT, load cell, personal computer, as well as XYZ-stages into a contact force-controlled SPM

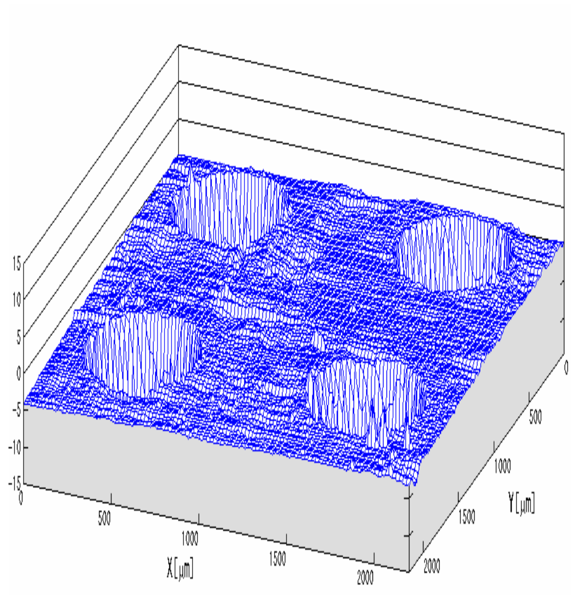


Fig.23 The profiler of a BGA substrate with ET-4000.

system, such that the surface of the sample would not be destroyed by the contact force produced by the stylus probe.This research applied both the traditional PI (Proportion and Integration) compensator and the fuzzy control methods for a Scanning Probe Microscope (SPM) system design. In addition, the actuator hysteresis effect was taken into consideration. It can be seen that the system performance obtained by the proposed fuzzy controller was much better, especially in eliminating the actuator hysteresis effect. This improvement has been verified by MATLAB simulation and practical implementation of a surface profiler.

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