行政院國家科學委員會專題研究計畫 成果報告

整合類神經網路及動態滑順模糊控制之可調接觸力垂直探針輪廓儀設計(第2年)

研究成果報告(完整版)

計畫類別：個別型
計畫編號：NSC 97-2221-E-216-013-MY2
執行期間：98年08月01日至99年07月31日
執行單位：中華大學機械工程學系

計畫主持人：林君明

報告附件：出席國際會議研究心得報告及發表論文

處理方式：本計畫涉及專利或其他智慧財產權，1年後可公開查詢

中 華 民 國 99年12月17日

附件一

行政院國家科學委員會補助專題研究計畫 ■成果報告 □期中進度報告

整合類神經網路及動態滑順模糊控制之可調接觸力垂直探針輪廓儀設計

計畫類別：■個別型計畫　□整合型計畫
計畫編號：NSC 97－2221－E－216－013－MY2
執行期間：　97 年 8 月 1 日至 99 年 7 月 31 日

執行機構及系所：中華大學通訊工程學系

計畫主持人：林君明
共同主持人：
計畫參與人員：侯忠慶、林俊杰、史廷揆、林政宏

成果報告類型(依經費核定清單規定繳交)：□精簡報告　■完整報告

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中　華　民　國　99 年　10 月　1 日

中文摘要

目前以音圈(Voice Coil)或是電磁裝置(Electromagnetic Device)，作為力致動器(Force Actuator)的趨勢，有快速增加的現象，這是因為它很便宜，且很容易驅動使用的緣故。但是這種音圈力致動器或電磁裝置，有很嚴重的非線性效應，例如死帶區(Dead Band)，及磁滯效應(Hysteresis Effect)。傳統設計這種非線性系統，是在工作點(Operating Point)的附近，將系統動態方程式進行線性化，再利用各種線性控制方法，進行控制器的設計。但是當系統參數有變化(Parameter Variation)，或是有負載干擾(Load Disturbance) ，或是有死帶區，或是有磁滯效應時，這些預先設計好(增益及補償器皆為固定式)的控制器，就不一定能使系統維持良好的反應，可能誤差會加大，甚至產生不穩定的現象，所以必須要找一個更有效的方法。本研究之可調接觸力輪廓儀設計，是以模糊控制理論，結合動態滑動模式控制(Dynamic Sliding Mode Control, DSMC)方法，建立系統的基本理論架構。以往是用PI補償器(未加入模糊控制器)進行掃描探針系統之設計，對力致動器的磁滯效應，有些改善效果。本研究是運用PID模糊控制器做為補償器，進行設計，發現結果比用傳統PI補償器所提出的方法，還要好，這是一個新的發現。

關鍵詞: 模糊類神經網路控制,動態滑動模式控制,音圈式力致動器,死帶區,磁滯效應.

英文摘要

This research is going to upgrade the previous work of a contact force- controlled scanning probe microscopy system design, which had main parts as: XYZ-stage, force actuator (voice coil) and driving circuit, Linear Variable Differential Transformer (LVDT), Linear Velocity Transducer (LVT), load cell (10 mg accuracy), diamond probe (1μm accuracy), data acquisition board, and operating system programming. The PID controller and LVT were applied to improve the inner-loop damping and the transient response of the system that would be degraded by the dead-band as well as the hysteresis effects of the force actuator, the contact-force of the probe was detected by a load cell and feedback to move the force actuator to make the desired contact-force between the probe and the sample under test. Thus the force actuator dead-band as well as the hysteresis effects can be minimized. Finally, the profile of the object surface is displayed on a 3D graph. The accuracy of the system was 1μm. The drawbacks of the previous method were that if one made a long time test, then the temperatures of the voice coil as well as the load cell would be increased. Thus not only the parameters of the system would be varied, but the load cell noise would be raised, then reducing the accuracy performance of the system. This research is to integrate PID type fuzzy controller with the Dynamic Sliding Mode Control (DSMC) to make the system more robust to the dead-band as well as the hysteresis effects of the force actuator. Comparisons with a previous design with PI compensator are also made. This method is more robust than PI compensator. In addition, this idea has been verified by practical implementation of a surface profiler to reduce the hysteresis effect of the force actuator.

Keywords: Fuzzy Neural-Network Control, Dynamic Sliding Mode Control, Voice Coil Force Actuator, Dead-band, Hysteresis Effect.

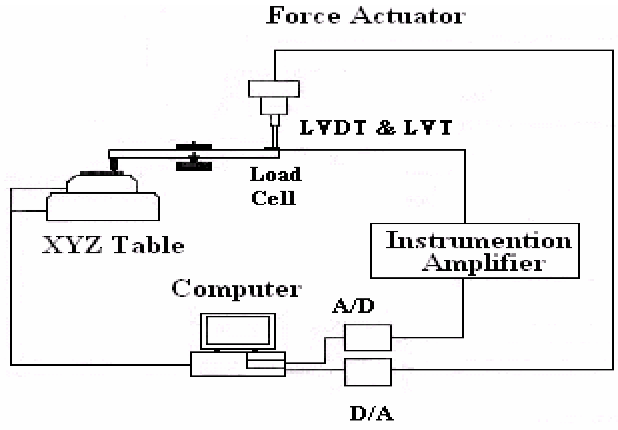
前言

由於我國目前正大力推動兩兆雙星產業，所以投入大量資金，購買設備與訓練高科技人才。21世紀高科技產品之開發趨勢，更是朝向超微小材料結構方向發展。此時亟需正確量測與描述奈米材料物理性質之儀器，如半導體、光電、及硬碟製造技術，不斷推陳出新，有一個共同的特徵：就是對加工物表面的平坦，或輪廓的要求越來越高[1-19]。例如半導體晶圓在進行金屬化連線製程之前，需要先做平坦化處理（CMP），以確保金屬連線後的可靠度。而硬碟讀取頭也需要在平坦度極高的磁碟片上飛行，進行資料快速的存取。而光電元件表面粗糙度，也是影響影像傳輸品質的重要因素。所以近來工業界對於各類表面輪廓儀的需求，是非常的殷切。值得我國儘速投入人力及設備進行研發。其中掃描探針顯微術(Scanning Probe Microscopy, SPM)，便是一個極具潛力的技術[9-19]。

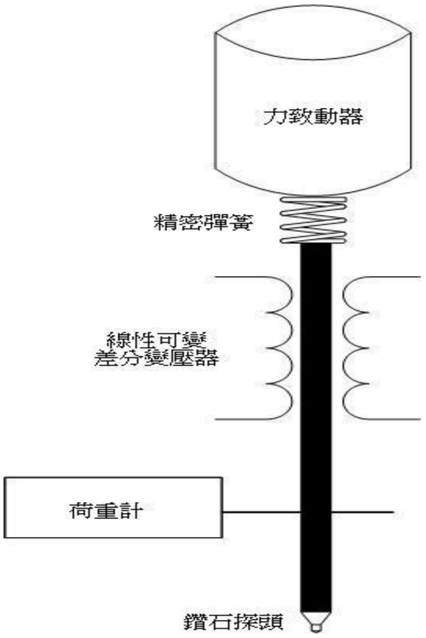
研究目的

由於SPM已在實驗室中，展現出搬移單原子，並製造原子尺寸材料結構的能力，也可在真空、空氣、水溶液等環境下操作，使得掃描探針顯微術，成為奈米科技的發展基礎，並受到全球科技界的重視。但是國內在發展高科技產業的同時，其中最重要的SPM等相關檢測設備，須向其他先進國家購買，不但設備價格高昂，維修不易，如果碰到競爭對手干預，則將會遭到設備出口管制問題。所以本研究是建立自製檢測設備的能力與基礎，而以發展接觸式掃描探針顯微系統為出發點。由於可控制接觸力之掃描探針顯微系統，複雜性比前述之SPM檢測設備低，環境容忍能力也較高。而檢測的精度可以利用機構的設計，數值處理的手法，以及電路方面的提升，而具有開發的潛力。

本計畫系統主要元件包括：XYZ移動平台[13]、音圈力致動器(Voice Coil Force Actuator)、線性可調式差分變壓器(LVDT， Linear Variable Differential Transformer)、荷重計(Load Cell) (精密度10毫克)、垂直鑽石探針頭(半徑 10μm)、驅動電路、訊號擷取卡，及自行研發的系統操作程式(Operating System Programming)。基本操作原理是先設定探針，與待測物的接觸力(如10毫克)，而後運用XYZ平台，進行平面掃描，配合荷重計，線性可變差分變壓器，類比/數位訊號擷取卡，以往是運用 PID控制器[20-22]，進行系統補償，將荷重計的訊號處理後回授，再將誤差訊號，傳到力致動器，做施力誤差補償。系統硬體架構連結，如圖1。最後是將擷取到的數位資料，利用軟體程式，以畫面呈現在電腦螢幕上。



(a) 架構圖



(b) 系統硬體圖

圖 1　可控制接觸力之掃描探針顯微系統(a)架構圖及(b)硬體圖

運用音圈(Voice Coil) 或是電磁裝置(Electromagnetic Device)，作為力致動器(Force Actuator)的趨勢，有快速增加的現象，這是因為它比壓電致動器便宜[23]，且很容易驅動使用的緣故。但是由圖 2 可知這種音圈或電磁裝置，有很嚴重的非線性效應，例如死帶區(Dead Band)及磁滯效應(Hysteresis Effect) 。傳統設計這種非線性系統，是在工作點(Operating Point)的附近，將系統動態方程式進行線性化，再利用各種線性控制方法，進行控制器的設計。例如 PID(如圖 3)，相位領先(Phase Lead)，相位落後(Phase Lag)，狀態回授(State Feedback)，及極點配置(Pole Placement)等補償控制器[24]。而後再看若系統參數有變化(Parameter Variation)，或是有負載干擾(Load Disturbance) ，或是有死帶區，或是有磁滯效應時，這些預先設計好(增益及補償器皆為固定式)的控制器的反應，若誤差會加大，甚至產生不穩定的現象，則再找一個更有效的方法。

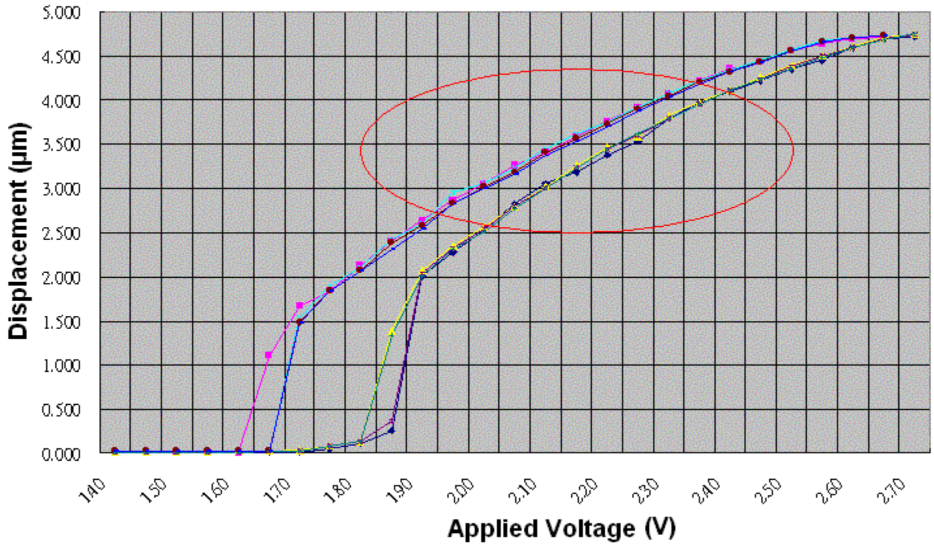


圖 2 磁滯效應曲線的對照圖

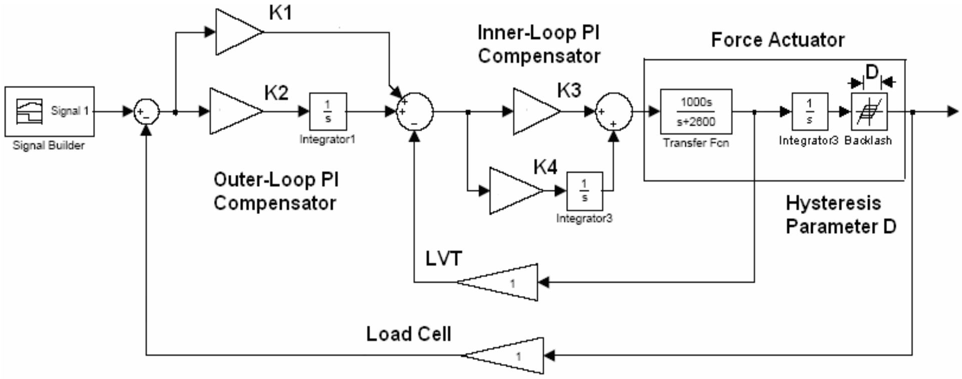


圖 3　PID 控制器方塊圖

因為 PID 控制器中的微分控制器，若有雜訊，則會造成雜訊放大效應，而沒有採用。所以只有用到 PI 控制器。依據傳統控制理論，可得六組 K1，K2，K3 及 K4 的幾個代表性結果，各對應組合之內、外迴路增裕邊限，相位邊限(Gain and Phase Margin) ，及相位穿越頻率(Phase Cross-over Frequency ω_c) ，對照如表 1。

表 1 PI 控制器各對應增益組合之增裕及相位邊限對照表

Case	K1	K2	K3	K4	GM1	PM1(Deg)	GM2	PM2(Deg)	ω_c(r/sec)
1	12	120	1	200	∞	73	∞	85	9840
2	10	100	0.8	180	∞	75	∞	70	7500
3	15	100	1.5	200	∞	65	∞	88	20000
4	20	150	2	150	∞	63	∞	89.5	40000
5	8	80	0.5	300	∞	85	∞	60	30000
6	18	200	1.3	220	∞	70	∞	90	30000

若系統輸入命令為三角波，如圖 4；則情況 1，2，5 及 6 的輸出響應，可得如圖 5-8。可知當力致動器有死帶區(Dead Band)，及磁滯效應(Hysteresis Effect)等非線性效應時(D=0.1)，則上述即使是增裕及相位邊限都不錯的設計，其輸出仍然有很嚴重的磁滯效應。

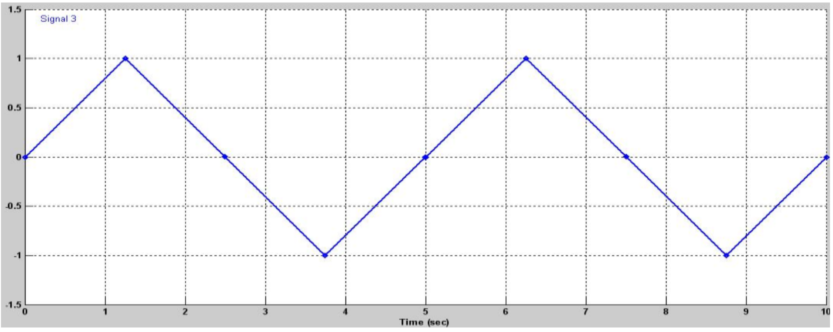


圖 4　輸入三角波示意圖

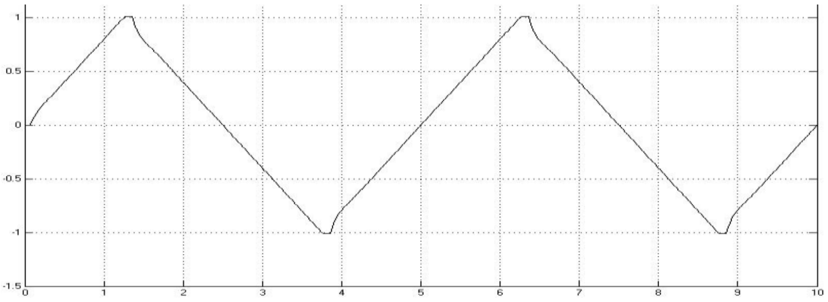


圖 5　情況 1 之輸出三角波示意圖(D=0.1)

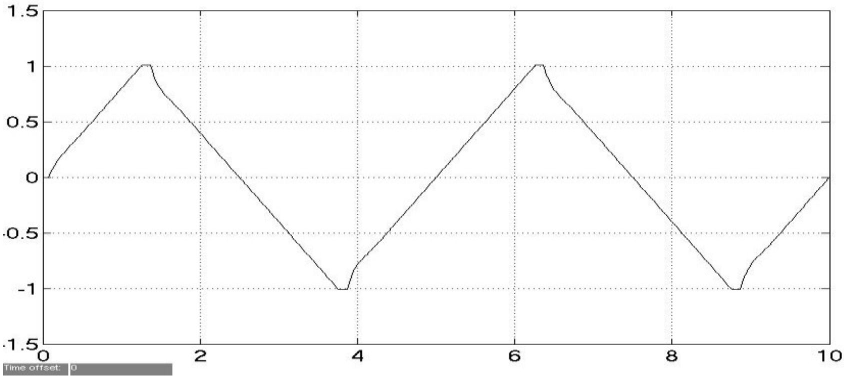


圖 6　情況 2 之輸出三角波示意圖(D=0.1)

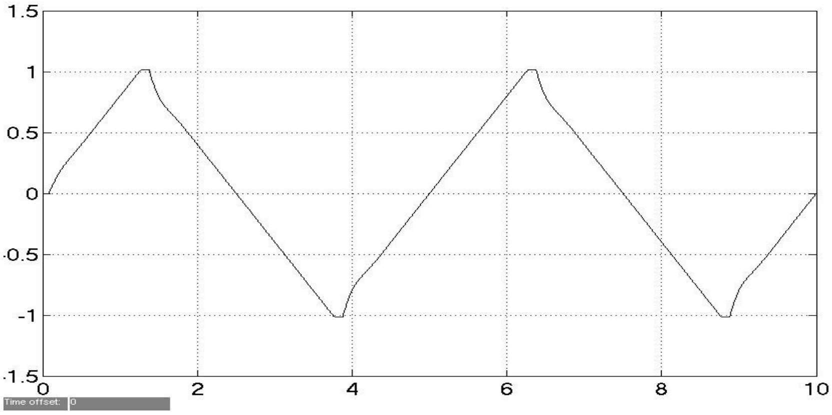


圖 7　情況 5 之輸出三角波示意圖(D=0.1)

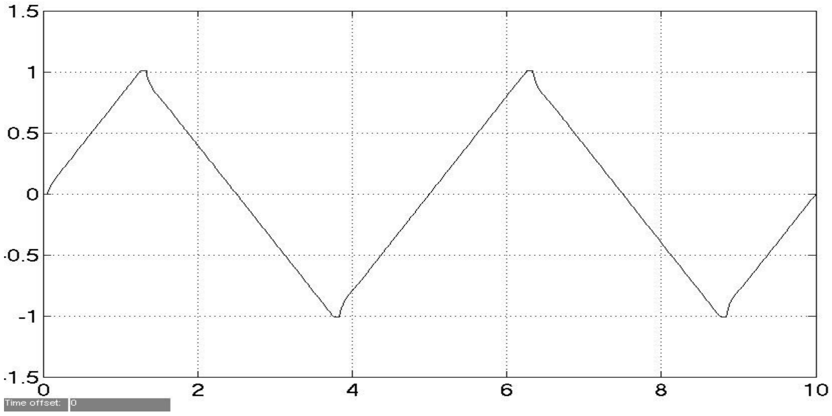


圖 8　情況 6 之輸出三角波示意圖(D=0.1)

所以本計畫想運用模糊控制及滑動模式控制，來解決上述力致動器的非線性效應，例如死帶區(Dead Band)及磁滯效應(Hysteresis Effect)問題。

研究方法

一般非線性系統設計法[25]可分為：H∞控制[25]，滑動模式控制(Sliding Mode Control, SMC)[26-34]，模糊控制[35-64]，及回授線性化控制，其中以滑動模式，及模糊控制為最常見。滑動模式控制的主要特色，是利用不連續的控制輸入，使系統狀態能確保於切換平面(Switching Plane)附近，並沿著切換平面滑動至原點，使受控體(Plant)不受系統參數變化，及外在負載干擾的影響。

模糊控制主要是針對已知，或未知的非線性成分，依據模糊變數，及模糊控制準則，來消除非線性成分，且系統模型不需很準確，即可達成強健控制之目的。因此本次研究第一年，是以MATLAB套裝軟體[65]，進行滑動模式控制、模糊理論推導、整合及模擬分析。另一方面則是整合TMS320F2018數位信號處理器的軟體及硬體架構[66-68]，與可調接觸力垂直探針輪廓儀硬體系統，並進行界面電路的設計分析。第二年則是將第一年推導的滑動模式控制、模糊理論法則，藉著套裝軟體(C+ Composer Studio, CCS) ，進行TMS320F2018數位信號處理器，C語言的程式轉換及設計，與可調接觸力垂直探針輪廓儀界面電路的製作。最後進行及軟體及硬體整合測試。模糊控制進行步驟摘要如下：

步驟 1 模糊規則庫設計
步驟 2 模糊控制系統設計
步驟 3 模糊系統處理過程設計
步驟4 解模糊化設計

模糊控制系統設計

模糊控制理論自Lotfi Zadeh 於1965 創始以來，已被廣泛應用於各個領域，它被證明是個出色的方法用來處理繁雜的非線性系統。系統方塊如圖9。若迴路追蹤誤差為E，誤差變化為ΔE，則模糊規則庫之設計，是運用下列IF-THEN 法則，定義出以下控制規則：

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，

其中 NB，NM，NS，ZE，PS，PM 及 PB，分別表示大的負值，中的負值，小的負值，零，小的正值，中的正值，及大的正值。表 2 為追蹤誤差 E，ΔE 及輸出 U 之模糊規則庫對照表。而表 3-5 為追蹤誤差 E，ΔE，及輸出 U 之三角形歸屬函數對照表，其圖形如圖 10-12。

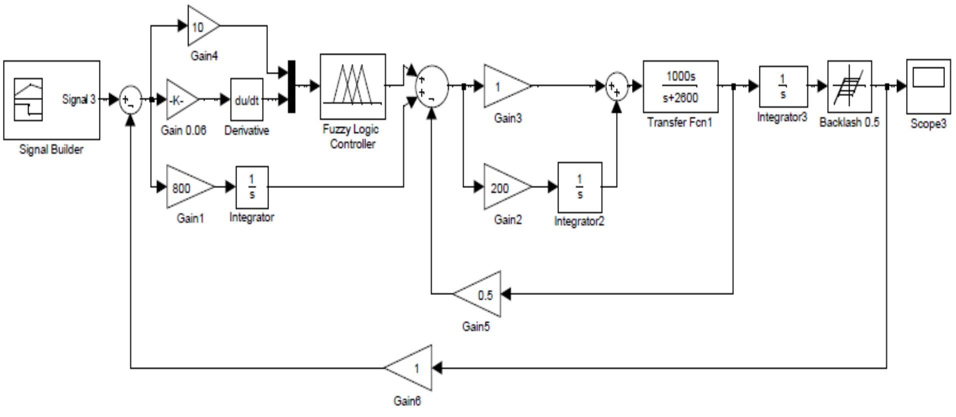


圖9 本研究所使用的PID模糊控制器系統方塊圖

表2　模糊控制輸入E，ΔE及輸出U之模糊規則庫對照表

E, ΔE	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

表 3 追蹤誤差 E 之三角形歸屬函數對照表

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]

表 4 追蹤誤差變率 ΔE 之三角形歸屬函數對照表

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 4.5 4.5]

表 5 輸出 U 之三角形歸屬函數表對照表

Item	Type	Parameter
Negative Big (NB)	Trapmf	[-12 -12 -9.6 -8.4]
Negative Medium (NM)	Trimf	[-9.6 -8.4 -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]

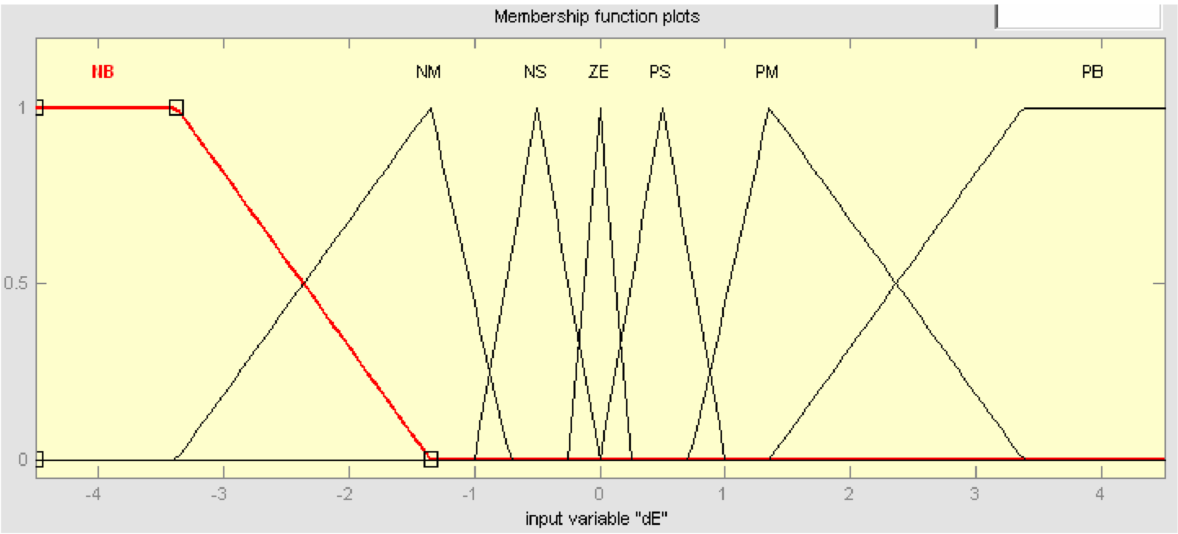


圖 10　E 之三角形歸屬函數示意圖

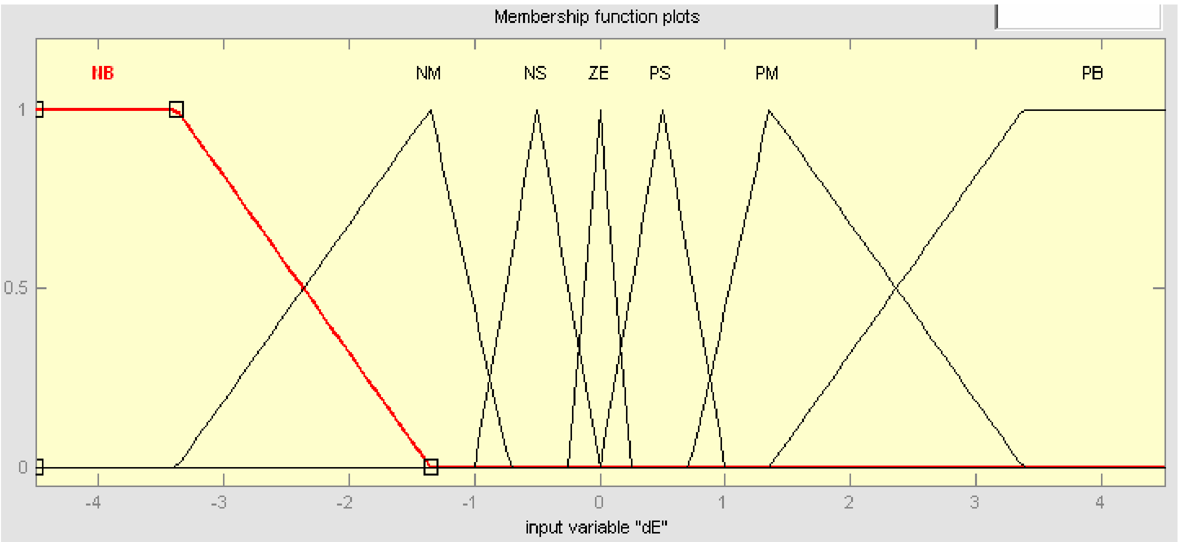


圖 11 追蹤誤差變率 ΔE 之三角形歸屬函數

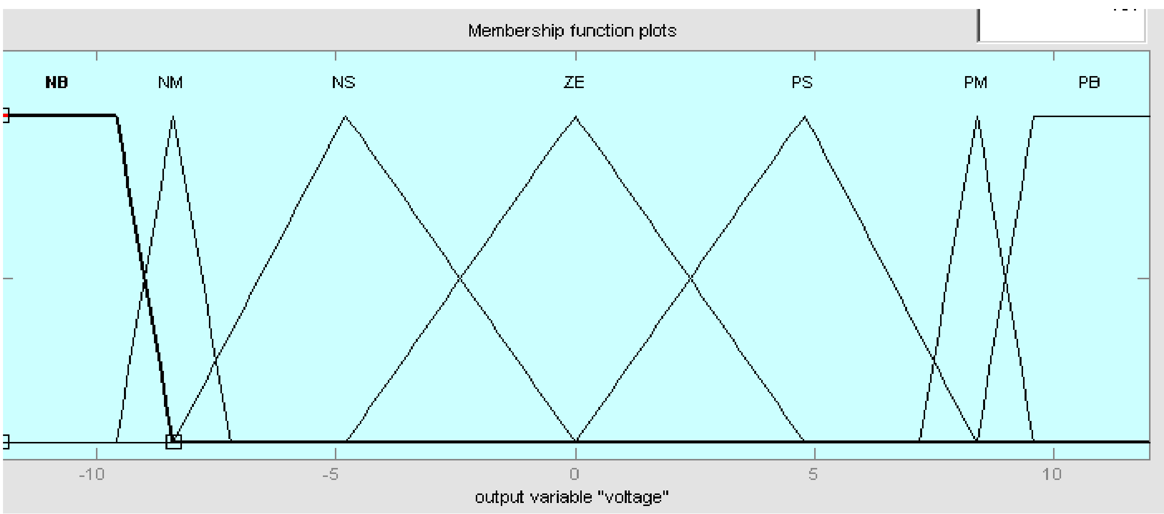


圖 12 輸出 U 之三角形歸屬函數

使用此模糊控制器之三角波輸出響應，如圖 13 (D=0.1)。可見磁滯效應已獲得很大的改善。如將參數 D 放大為 0.3 及 0.5，則系統響應如圖 14 及 15。可見系統響應仍然非常好，可見模糊控制其的確是可以降低力致動器的磁滯效應。

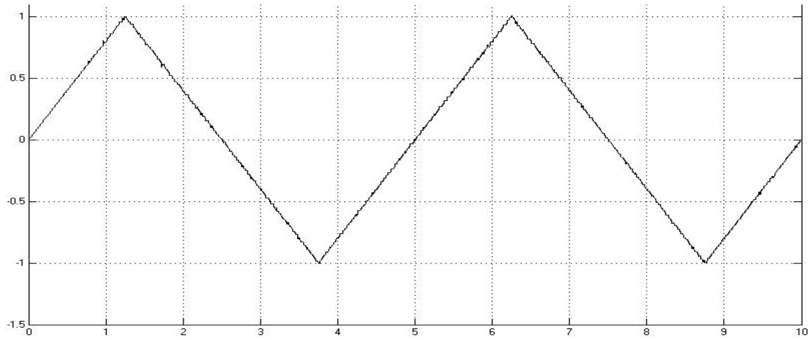


圖 13 模糊控制器之三角波輸出響應圖(D=0.1)

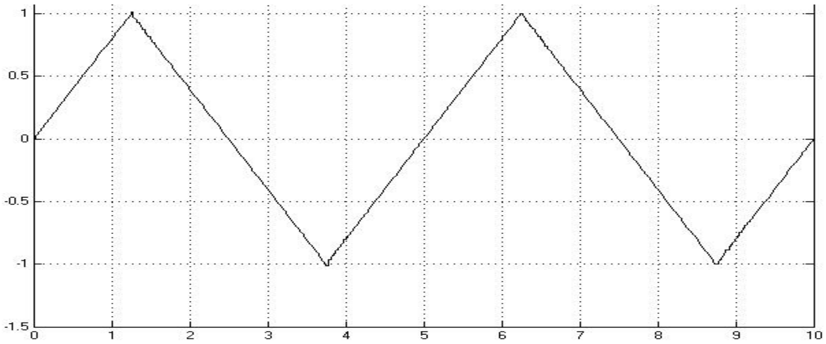


圖 14 模糊控制器之三角波輸出響應圖(D=0.3)

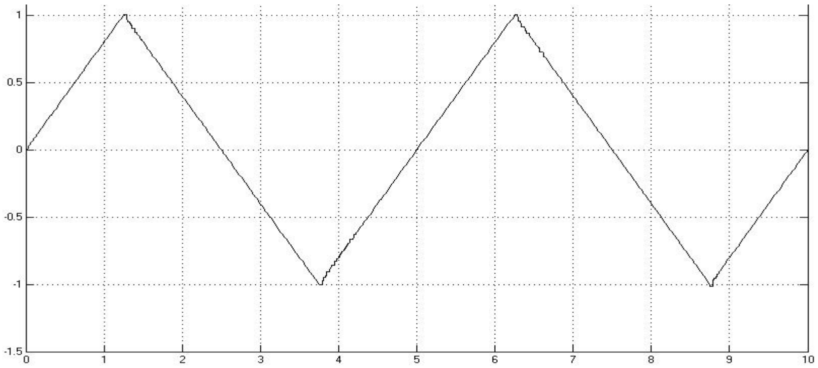


圖 15 模糊控制器之三角波輸出響應圖(D=0.5)

此外本計畫也有以參考文獻[68]所提，將模糊控制器做為前饋式補償器(Feed-forward Loop Compensator)，如圖 16 進行設計。其好處是不會影響原來運用 PID 方法，設計出來的系統穩定性。致動器之死區(Dead Zone)參數 D 設定為 0.1 及 0.5，但是系統之反應並不好，模擬之結果如圖 17 及 18。將於後續計畫進行研究，如可將傳統的 PID 補償器先設計好，而後直接轉成 PID 模糊控制器，則可保持原系統的相對穩定度。

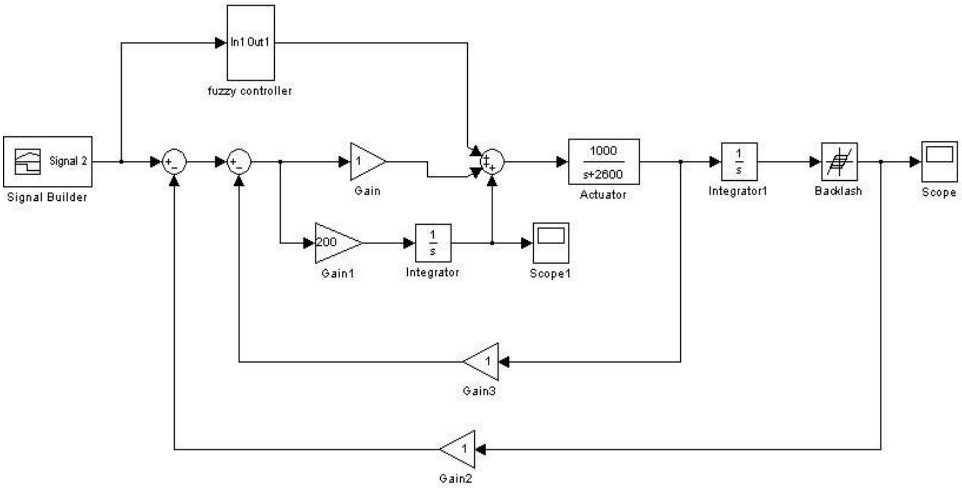


圖 16 以模糊控制器作為前饋式補償器進行設計之模擬方塊圖

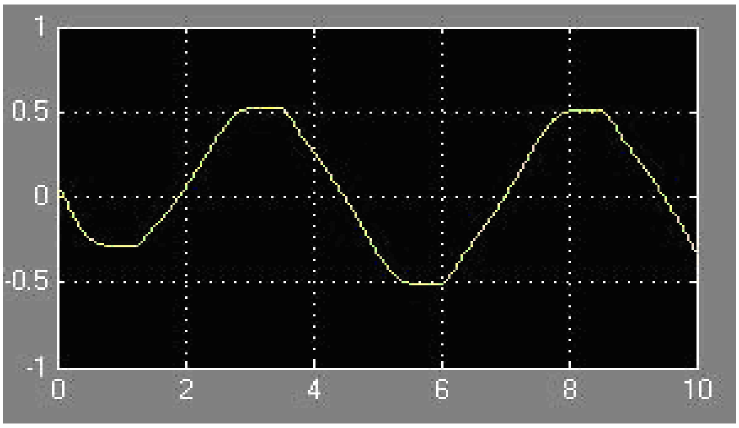


圖 17 以前饋式補償器進行設計之三角波輸出響應圖(D=0.1)

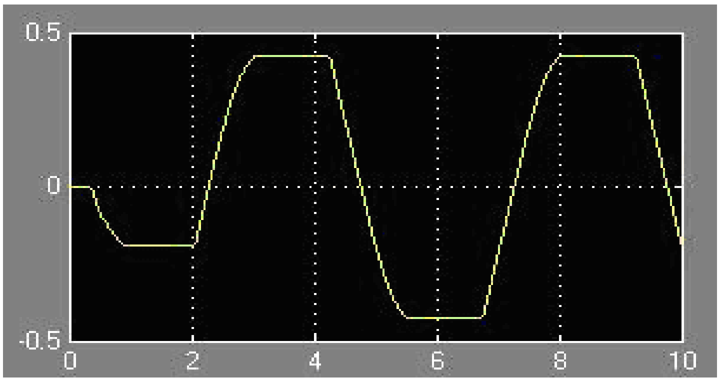


圖 18 以前饋式補償器進行設計之三角波輸出響應圖 (D=0.5)

最後將本計畫所研發的模糊控制器法則，燒入計算機，進行樣品的輪廓量測，其結果如圖 19 及 20，如運用一般市面上的輪廓儀(ET4000)進行量測，其結果如圖 21。可見本系統的成果已有相當的效果。

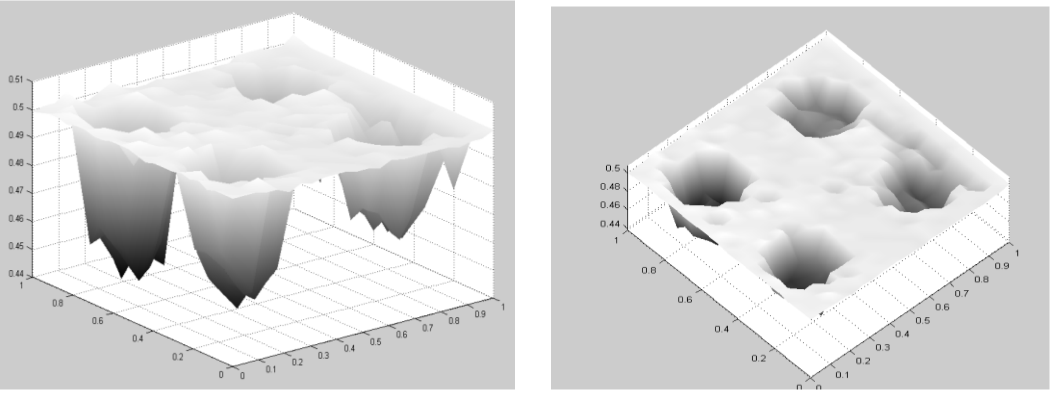


圖 19 樣品的輪廓量測結果

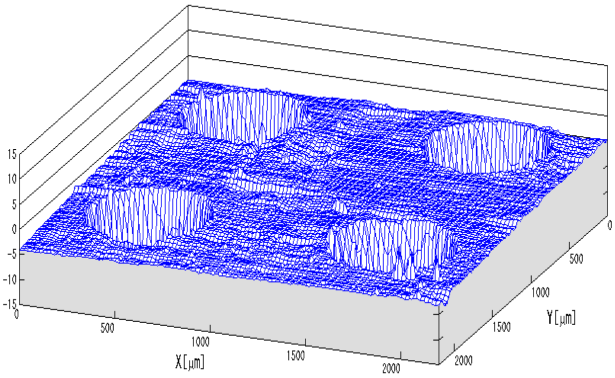


圖 20 運用一般市面上的輪廓儀(ET4000)量測樣品的輪廓

討論

目前以音圈(Voice Coil)或是電磁裝置(Electromagnetic Device)，作為力致動器(Force Actuator)的趨勢，有快速增加的現象，這是因為它很便宜，且很容易驅動使用的緣故。但是這種音圈力致動器或電磁裝置，有很嚴重的非線性效應，例如死帶區(Dead Band)及磁滯效應(Hysteresis Effect)。傳統設計這種非線性系統，是在工作點(Operating Point)的附近，將系統動態方程式進行線性化，再利用各種線性控制方法，進行控制器的設計。但是當系統參數有變化(Parameter Variation)，或是有負載干擾(Load Disturbance) ，或是有死帶區，或是有磁滯效應時，這些預先設計好(增益及補償器皆為固定式)的控制器，就不一定能使系統維持良好的反應，可能誤差會加大，甚至產生不穩定的現象，所以必須要找一個更有效的方法。本研究之可調接觸力輪廓儀設計，是以模糊控制理論，結合動態滑動模式控制(Dynamic Sliding Mode Control, DSMC)方法，建立系統的基本理論架構。其中控制法是以滑動模式控制、模糊理論推導方式獲得。以往是用 PI 補償器(未加入模糊控制器)進行掃描探針系統之設計模擬，對力致動器的磁滯效應有些改善效果。本研究是運用 PID 模糊控制器做為補償器，進行設計，發現結果比用 PI 補償器所提出的方法，還要好，這是一個新的發現。

致謝

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INTELLIGENT FUZZY PID CONTROLLER DESIGN OF A SCANNING PROBE MICROSCOPE SYSTEM

Po-Kuang Chang [a], and Jium-Ming Lin [b*]
[a] Ph.D. Program in the Institute of Engineering Science, Chung-Hua University, Taiwan
E-MAIL: puppy@itri.org.tw
[b] Department of Communication Engineering, Chung-Hua University, Hsin-Chu, Taiwan
(TEL : +886-3-518-6483; E-MAIL: jmlin@chu.edu.tw)

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Abstract: This research is to use an intelligent PID type fuzzy controller for a scanning probe microscope system design. Comparisons with a previous design with PI compensator are also made by simulation. In addition, this idea has been verified by practical implementation of a surface profiler to reduce the hysteresis effect of the force actuator.

Keywords: LVT, LVDT, load cell, surface profiler, PID type intelligent fuzzy controller, hysteresis effect.

1. Introduction

The Scanning Probe Microscopy (SPM) has been developed rapidly in the last two decade [1-13]. Its usage is very extensive, for example, the measurements of physical distribution and material property such as surface profile, roughness, static charge, magnetic dipole, friction, elasticity, and thermal conductivity. As shown in Fig.1 for the system structure of a previous research [14] with PI controller, a balance with stylus probe, force actuator, LVDT (Linear Variable Differential Trans former), Linear Velocity Transducer (LVT), 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 of the stylus probe. This research is to use an intelligent fuzzy PID controller [15-17]. This improvement is better than the previous one, and has been verified by MATLAB simulation and practical implementation of a surface profiler to reduce the hysteresis effect of the force actuator.

The stylus probe is shown in Fig.3. The voice coil is applied as a force actuator (Fig.4), which is integrated with LVT and LVDT (Fig.5) to measure the probe vertical displacement and velocity. The load cell in Fig. 6 is used to detect the contact force between the probe and sample to be tested. A leaf spring in Fig.7 is applied to integrate the load cell with voice coil, LVT and LVDT module, the structure of probe module installation and the practical implementation are as shown in Figs. 8(a) and 8(b).

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[*] Corresponding author: Department of Communication Engineering, Chung-Hua University, Hsin-Chu, Taiwan, Tel: +886-3-518-6483; E-mail: jmlin@chu.edu.tw.

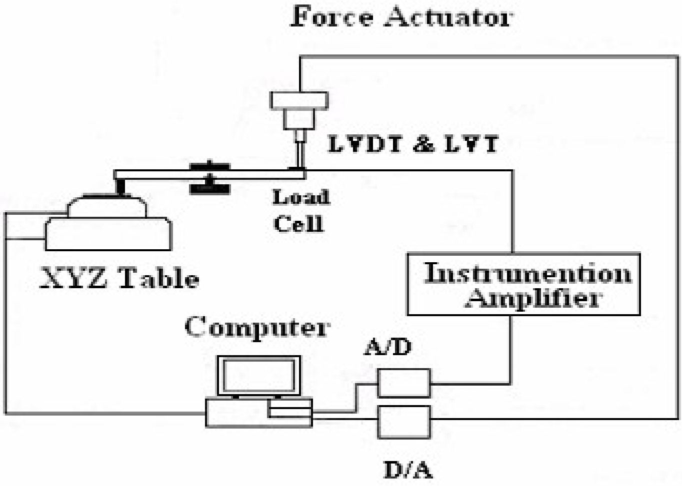


Fig. 1. The structure of a previous contact force-controlled SPM system.

Fig. 2. LVT.

Fig. 3. Stylus probe.

Fig. 4. Voice coil.

Fig. 5. LVDT.

Fig. 6. Load cell

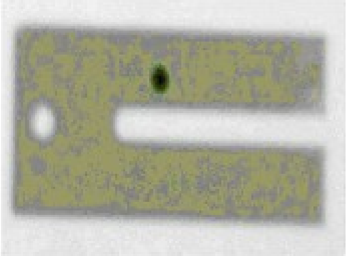
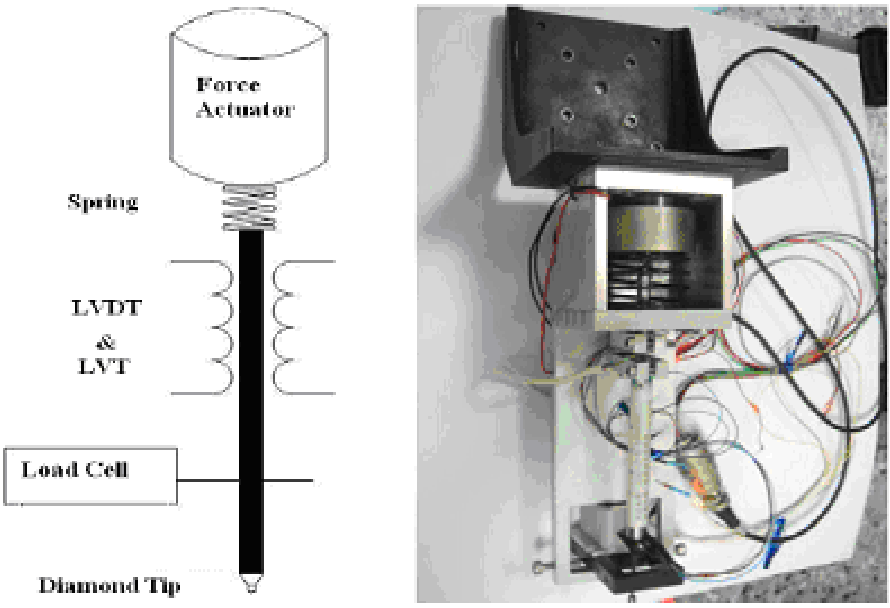


Fig. 7. Leaf spring

In addition to the XYZ-stages a piezo-stage in Fig. 9 is also put on the Z-stage to improve the measurement accuracy and initial point setting. The personal computer is the central control unit for the whole system, such as setting contact force between probe and the sample, taking contact force information from load cell, as well as driving the force actuator for balance-arm initial leveling. Thus it is an automatic SPM system.

The block diagram of the previous PI compensator system design [14] is with LVT for inner-loop feedback as shown in Fig. 10. However, the force actuator hysteresis effect cannot be reduced for larger D's of hysteresis effect parameter. To eliminate the hysteresis effect this research applied PID type intelligent fuzzy controllers [15-17]. This improvement has been verified by MATLAB simulation and practical implementation of a surface profiler. Comparisons with the previous PI compensator system design are also made.



(a) (b)

Fig. 8. The probe module is integrated by voice coil, LVDT, LVT, load cell and leaf spring. (a). Structure of installation. (b). Practical implementation.

Fig. 9. Piezo-stage and sample holder.

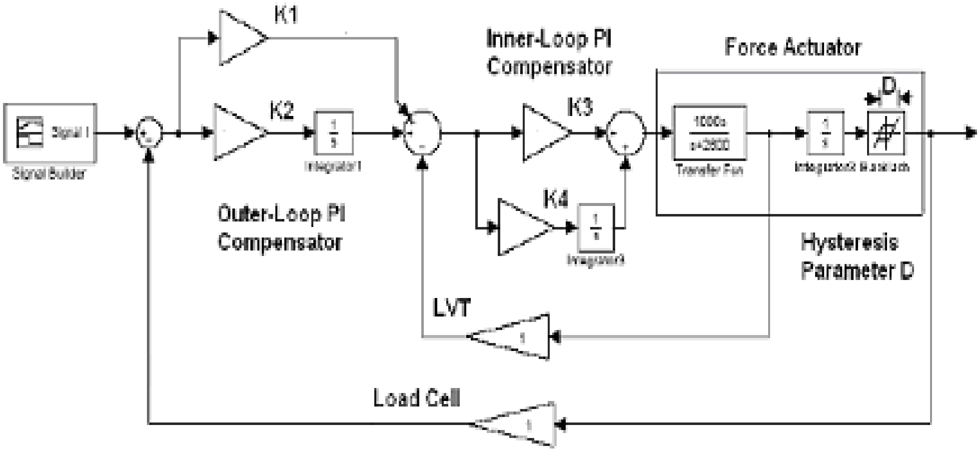


Fig. 10. Block diagram of a SPM system with PI compensator in the previous research

The organization of this paper is as follows: the first section is introduction. The second and the third ones are for the review of previous research and the proposed PID type fuzzy controller design. The test results and discussions are given in Section 4. The last part is the conclusion.

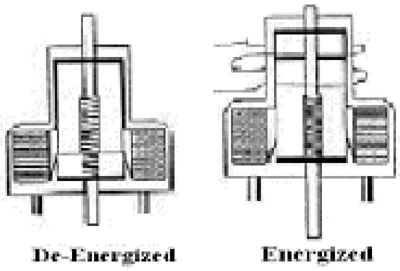
2. Review of Previous System Design

The structure of the previous SPM system [14] is shown in Fig.1. The major part is the balance. The stylus probe is on the left side, while force actuator and load cell are on the right side. The force actuator is consisted of a coil and a spring. As in Fig.11 (a) the rod returns to initial place when force actuator is de-energized. However, if a voltage is applied across the coil, then current flows in the coil, and a force would be generated to compress the spring and make the rod pull down as in Fig.11 (b). The relationship of the applied voltage and displacement is shown in Fig.12. The block diagram of the SPM in the previous research is as in Fig. 10. Table 1 listed some PI compensators design, in which, the corresponding gain margins, phase margins of the inner (GM1, PM1) and outer (GM2, PM2) loops as well as the phase cross-over frequencies ω_c are also listed.

Table 1. The results of the previous PI compensator design in Fig. 10.

Case	K1	K2	K3	K4	GM1	PM1 (Deg)	GM2	PM2 (Deg)	ω_c (r/sec)
1	12	120	1	200	∞	73	∞	85	9840
2	10	100	0.8	180	∞	75	∞	70	7500
3	15	100	1.5	200	∞	65	∞	88	20000
4	20	150	2	150	∞	63	∞	89.5	40000
5	8	80	0.5	300	∞	85	∞	60	30000
6	18	200	1.3	220	∞	70	∞	90	30000

To evaluate the results of design, a saw tooth-shaped command (period 5 seconds) as in Fig.13 is applied to the input of the system. The output responses of cases 1, 2, 5 and 6 for the system with hysteresis effect (backlash parameter D=0.1) are shown in Figs.14 -17. 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.



(a) (b)

Fig. 11. De-energized and energized states of force actuator. (a.) De-energized state. (b). Energized state.

The reason is that ω_c are very large for these cases, and then the time and phase delays produced by the hysteresis effect would be increased. Thus the stability can even be degraded by adding the hysteresis effect to push the resulting phase margins approaching zero.

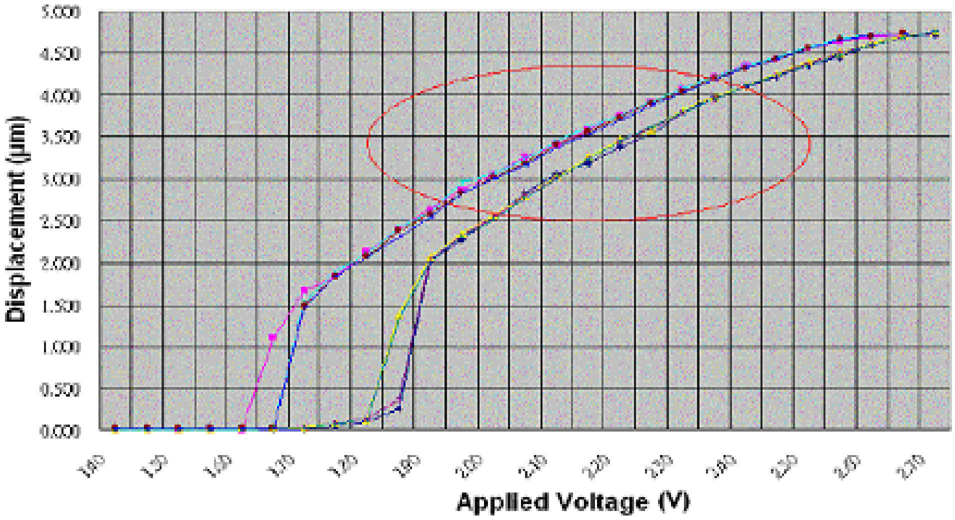


Fig. 12. Force actuator applied voltage vs. displacement.

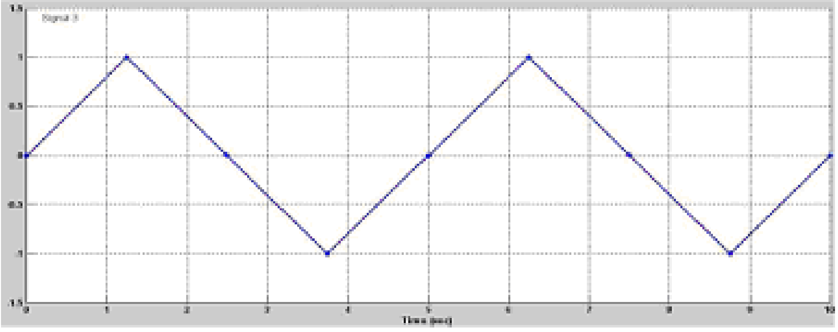


Fig. 13. A saw tooth command input.

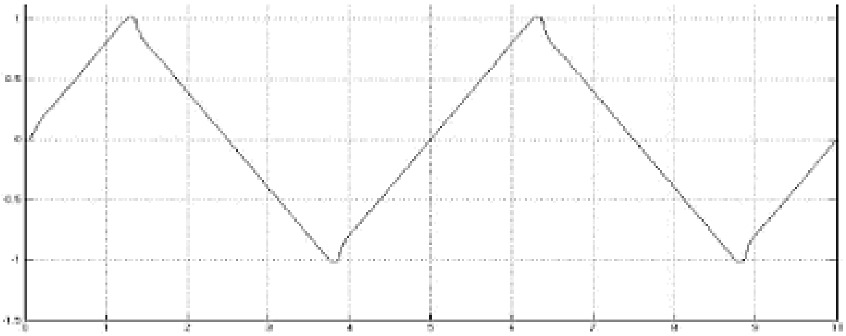


Fig. 14. Output of case 1 for D = 0.1 in Fig.10.

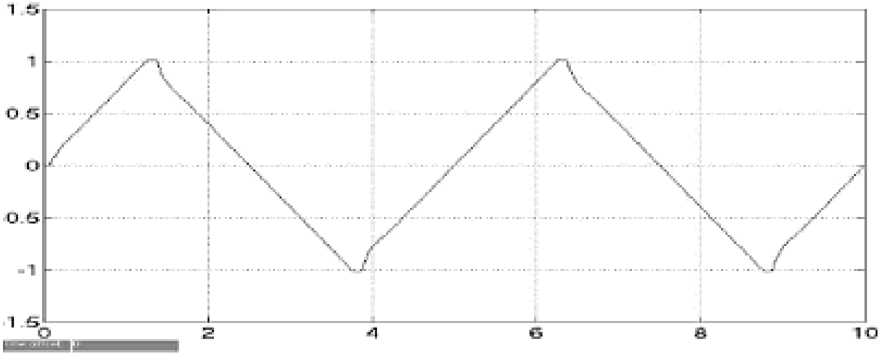


Fig. 15. Output of case 2 for D = 0.1 in Fig.10.

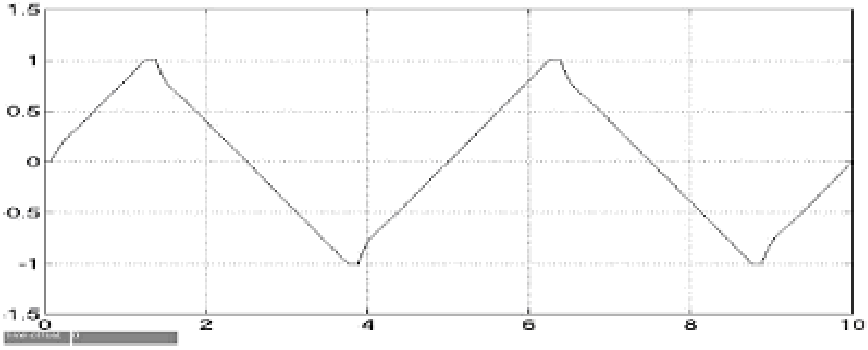


Fig. 16. Output of case 5 for D = 0.1 in Fig.10.

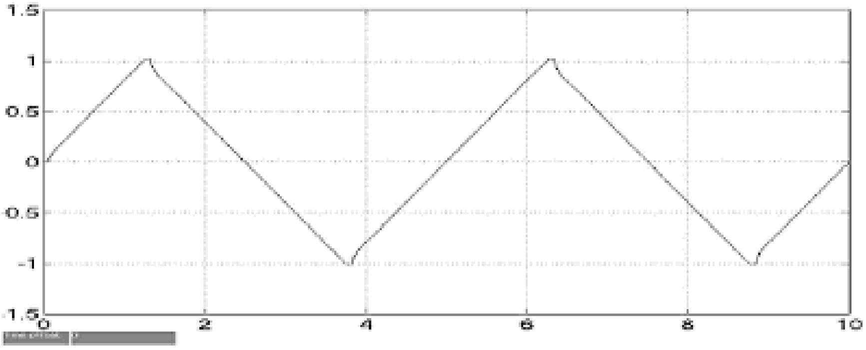


Fig. 17. Output of case 6 for D = 0.1 in Fig.10.

3. Fuzzy PID Controller Design

To reduce the hysteresis-effect this paper applies an intelligent fuzzy PID controller [15-17]; the block diagram of the control system is shown in Fig. 18. The fuzzy control design method is based on the IF-THEN RULE as follows:

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 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.

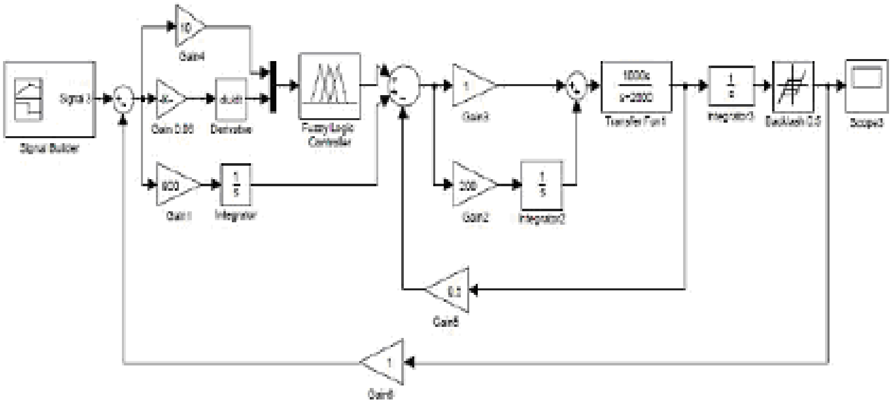


Fig. 18. The block diagram of an intelligent fuzzy PID controller for SPM system design.

The detailed cross reference rules for the inputs and output of PID type fuzzy controller are defined in Table 2. According to the fuzzy control design method the relationship functions of tracking error E, ΔE (deviations of present E and the previous E), and U (Control Input) are defined at first, which are listed in Tables 3-5 and also as shown in Figs. 19-21. In order to reduce the computation time, the triangular distribution functions are applied instead of Gaussian ones.

Table 2. Cross reference rules of PID type fuzzy controller.

E, ΔE	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

Then the performances obtained by PID type fuzzy controllers are analyzed by simulation. By some trial-and-error the proportion and integration gains are respectively set to 10 and 800 to speed up the response, and the gain of the derivative part is set to 0.06 to avoid the noise amplification problem. Fig. 22 shows the response for the backlash to be as 0.1. It can be seen that the result with D=0.1 is better than those obtained by the traditional PI controllers. Figs. 23-24 also show the responses for the backlash to be as 0.3 and 0.5, respectively. One can see the responses are still quite well, and the hysteresis problem can be reduced by the proposed method.

Table 3. Relationship functions of E in tabular form.

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 4. Relationship functions of ΔE in tabular form.

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 4.5 4.5]

Table 5. Relationship functions of U in tabular form.

Item	Type	Parameter
Negative Big (NB)	Trapmf	[-12 -12 -9.6 -8.4]
Negative Medium (NM)	Trimf	[-9.6 -8.4 -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]

4. Test Results and Discussions

The signal flow graph of the system operation steps is in Fig. 25 and summarized as follows. The first step is initial levelling of balance lever arm, which is achieved by adjusting the current through the force actuator coil. Since the lever arm weight at the stylus probe 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.

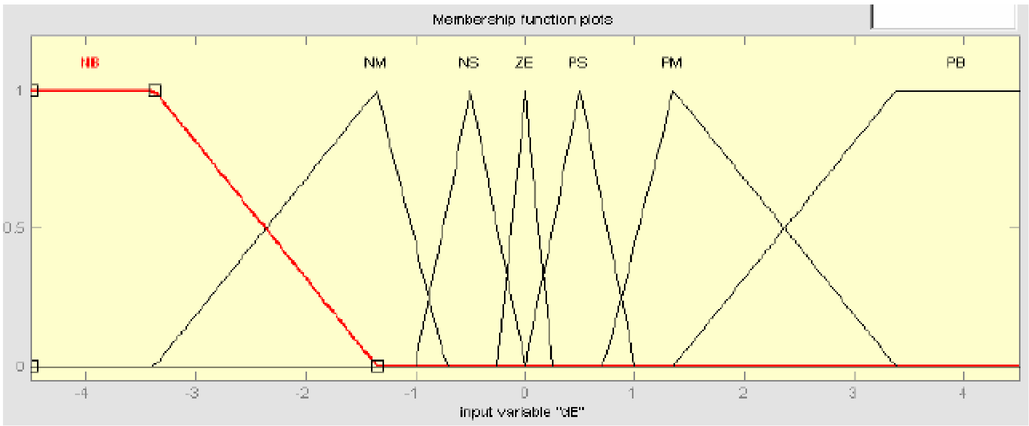


Fig. 19. Relationship functions of error E in figure form.

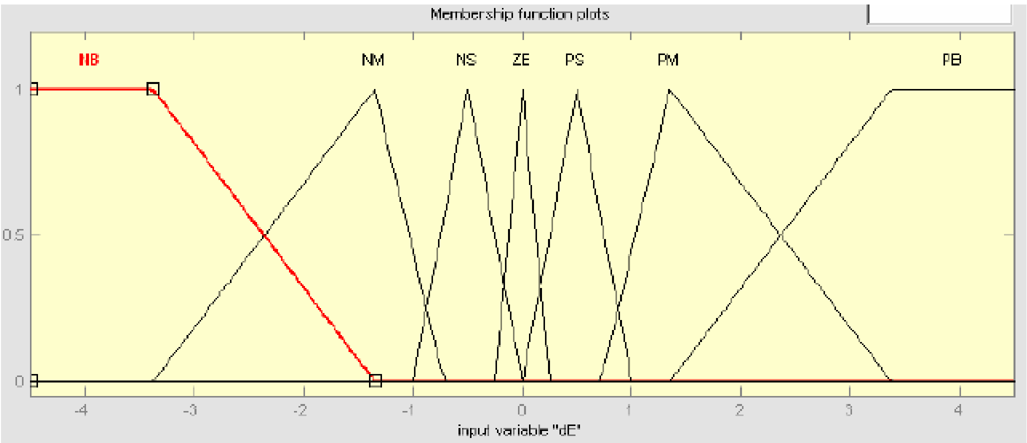


Fig. 20. Relationship functions of ΔE in figure form.

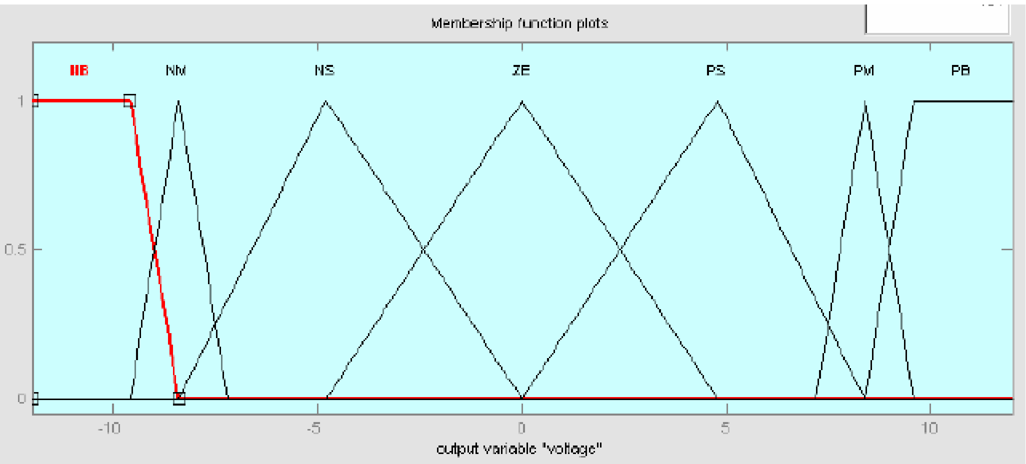


Fig. 21. Relationship functions of fuzzy controller output in figure form.

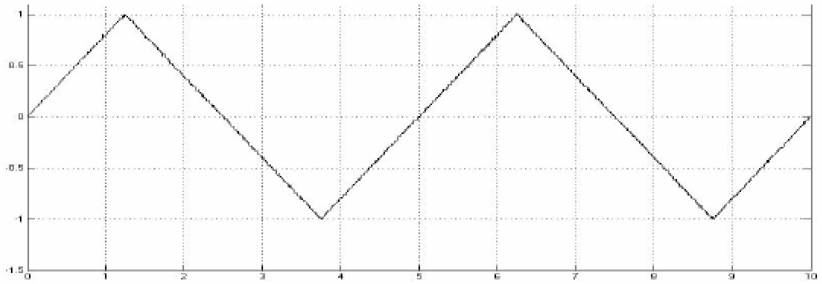


Fig. 22. Output with PID type fuzzy controller for D = 0.1.

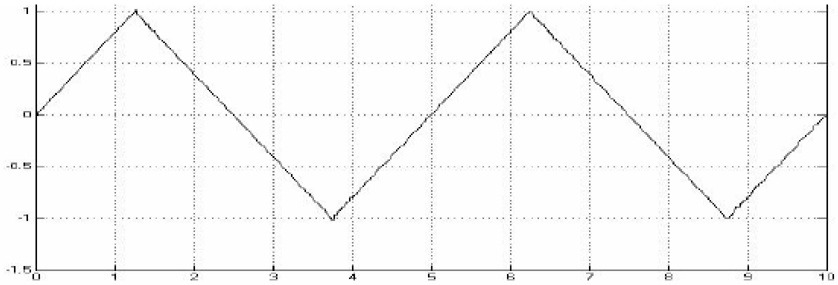


Fig. 23. Output with PID type fuzzy controller for D = 0.3.

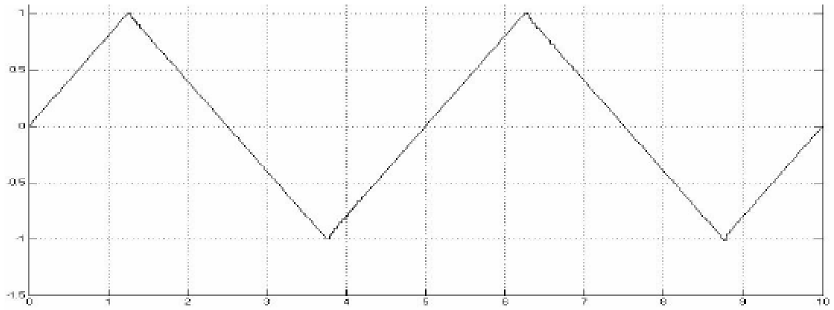


Fig. 24. Output with PID type fuzzy controller for D = 0.5.

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. 26. 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.

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. In order to make sure that the probe contacts with the sample while not destroy it, the maximum contact force is limited to 100 mg, i.e., if the magnitude of contact force is smaller than 100 mg, then moving the piezo-stage upward by one step (the resolution is 10 nm), otherwise, stop.

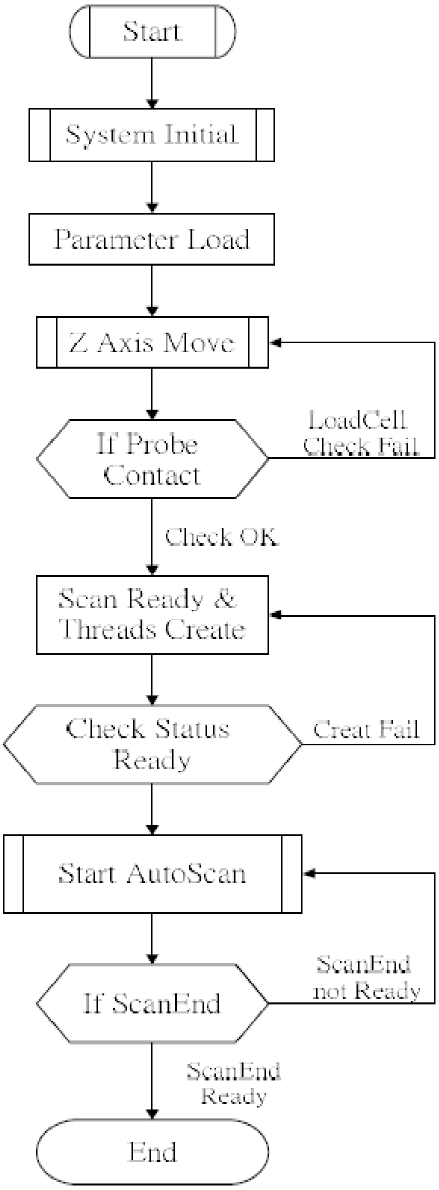


Fig. 25. The signal flow graph of the system operation.

Then by scanning the XY-stages in either x- or y-axis, and finally, the surface profile of the sample can be obtained as shown in Fig. 27 from LVDT. If one should like to see the top view, the result is shown in Fig. 28.

4. Conclusion

This research applied PID type fuzzy control for a Scanning Probe Microscope (SPM) system design. In addition, the actuator hysteresis effect was taken into consideration. Comparisons with a previous work with PI compensator are also made, it can be seen that the system performances obtained by the PID type fuzzy controller are much better, especially in eliminating the actuator hysteresis effect. This improvement has been verified by MATLAB simulation and practical implementation of a surface profiler. Finally, the profile of the object surface is displayed on a 3D graph.

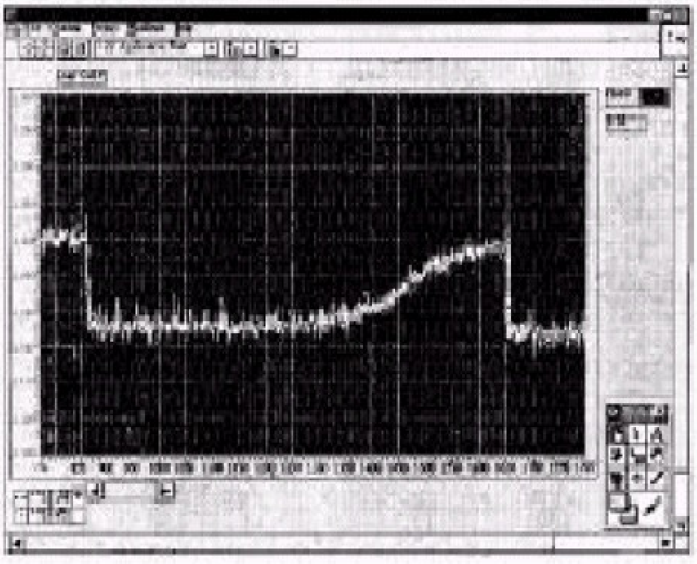


Fig. 26. Output voltage of the load cell is increased for the contact force changing from 0 mg to 40 mg.

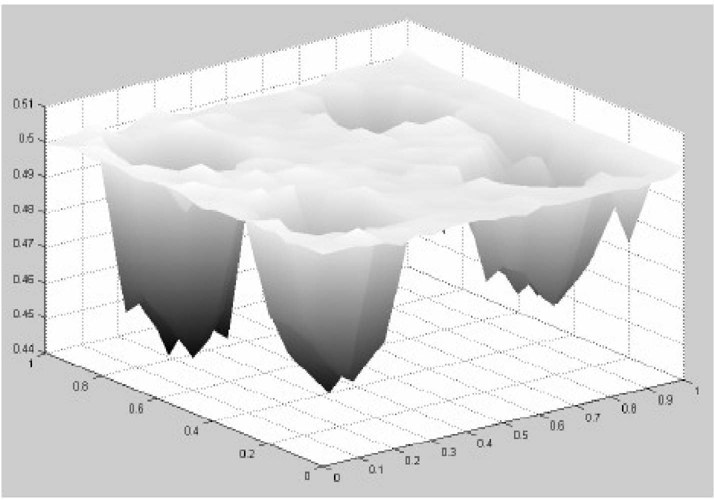


Fig. 27. The surface profile of a sample.

Acknowledgements

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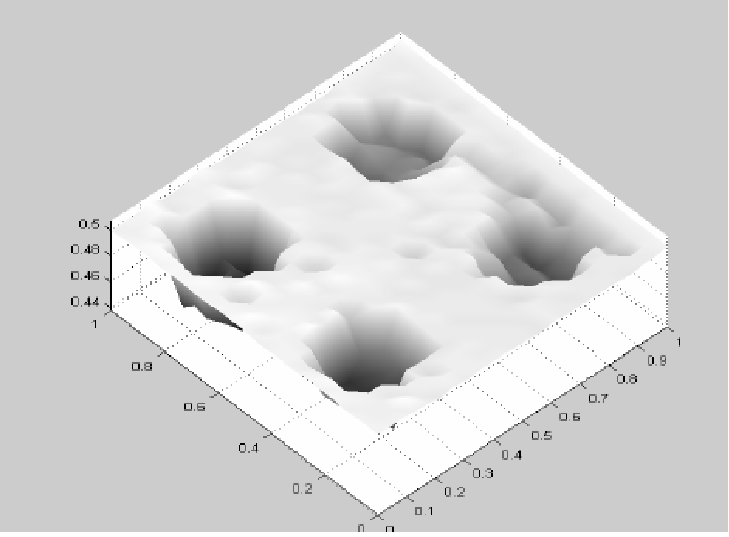

Fig. 28. The top view of the sample.

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附件二

國科會補助專題研究計畫成果報告自評表

請就研究內容與原計畫相符程度、達成預期目標情況、研究成果之學術或應用價值（簡要敘述成果所代表之意義、價值、影響或進一步發展之可能性）、是否適合在學術期刊發表或申請專利、主要發現或其他有關價值等，作一綜合評估。

1. 請就研究內容與原計畫相符程度、達成預期目標情況作一綜合評估

■ 達成目標

□ 未達成目標（請說明，以 100 字為限）

　□ 實驗失敗

　□ 因故實驗中斷

　□ 其他原因

說明：本研究之可調接觸力輪廓儀設計，是以模糊控制理論，結合動態滑動模式控制(Dynamic Sliding Mode Control, DSMC)方法，建立系統的基本理論架構。以往是用 PI 補償器(未加入模糊控制器)進行掃描探針系統之設計，對力致動器的磁滯效應有些改善效果。本研究是運用 PID 模糊控制器做為補償器，進行設計，發現結果比用傳統 PI 補償器所提出的方法，還要好，這是一個新的發現。

2. 研究成果在學術期刊發表或申請專利等情形：

論文：■已發表 □未發表之文稿 □撰寫中 □無

專利：□已獲得 □申請中 □無

技轉：□已技轉 □洽談中 □無

其他：(以 100 字為限)

本計畫研究成果，已被下列國際期刊接受

(1). Jium-Ming Lin and Po-Kuang Chang, “Applying Intelligent Fuzzy Control to Reduce Hysteresis Effect of Force Actuator in a SPM,” ***WSEAS Transactions on Systems and Control***, Vol.4, Issue 7, pp. 271-285, July 2009. (EI)

(2). Po-Kuang Chang and Jium-Ming Lin, “Intelligent Fuzzy Control of a Scanning Probe Microscope System Design,” ***ICIC Express Letters,*** Vol. 3, No. 4(A), pp. 951- 956, December 2009. (EI)

(3). Jium-Ming Lin and Po-Kuang Chang, “Eliminating Hysteresis Effect of Force Actuator in a SPM,” ***WSEAS Transactions on Systems and Control***, Vol. 5, Issue 1, pp. 1-15, January, 2010. (EI)

(4). Jium-Ming Lin and Po-Kuang Chang, “Integration both PI and PD Type Fuzzy Controllers for a Scanning Probe Microscope System Design,” ***WSEAS Transactions on Systems and Control*****, Volume 5, Issue 6,** pp. 484-497, June **2010 (EI).**

(5). Po-Kuang Chang and Jium-Ming Lin, “Intelligent Fuzzy PID Controller Design of a Scanning Probe Microscope System,” Accept for publication at **International Journal of Electronics, Electrical and Communication Engineering (IJEECE), 2010.**

3. 請依學術成就、技術創新、社會影響等方面，評估研究成果之學術或應用價值（簡要敘述成果所代表之意義、價值、影響或進一步發展之可能性）（以500字為限）

目前以音圈(Voice Coil)或是電磁裝置(Electromagnetic Device)，作為力致動器(Force Actuator)的趨勢，有快速增加的現象，這是因為它很便宜，且很容易驅動使用的緣故。但是這種音圈力致動器或電磁裝置，有很嚴重的非線性效應，例如死帶區(Dead Band)，及磁滯效應(Hysteresis Effect)。傳統設計這種非線性系統，是在工作點(Operating Point)的附近，將系統動態方程式進行線性化，再利用各種線性控制方法，進行控制器的設計。但是當系統參數有變化(Parameter Variation)，或是有負載干擾(Load Disturbance) ，或是有死帶區，或是有磁滯效應時，這些預先設計好(增益及補償器皆為固定式)的控制器，就不一定能使系統維持良好的反應，可能誤差會加大，甚至產生不穩定的現象，所以必須要找一個更有效的方法。本研究之可調接觸力輪廓儀設計，是以模糊控制理論，結合動態滑動模式控制(Dynamic Sliding Mode Control, DSMC)方法，建立系統的基本理論架構。以往是用 PI 補償器(未加入模糊控制器)進行掃描探針系統之設計，對力致動器的磁滯效應，有些改善效果。本研究是運用PID模糊控制器做為補償器，進行設計，發現結果比用傳統PI補償器所提出的方法，還要好，這是一個新的發現。

附件三

國科會補助計畫衍生研發成果推廣資料表

日期：99 年 10 月 1 日

國科會補助計畫	計畫名稱：整合類神經網路及動態滑順模糊控制之可調接觸力垂直探針輪廓儀設計 計畫主持人：林君明 計畫編號：NSC 97－2221－E－216－013－MY2 領域：精密控制及量測		
研發成果名稱	（中文）整合類神經網路及動態滑順模糊控制之可調接觸力垂直探針輪廓儀設計 （英文） Scanning Probe Microscope Design for Voice Coil Force Actuator with Fuzzy and Dynamic Sliding Mode Controller		
成果歸屬機構	中華大學	**發明人（創作人）**	林君明
技術說明	（中文） 本研究之可調接觸力輪廓儀設計，是以模糊控制理論，結合動態滑動模式控制(Dynamic Sliding Mode Control, DSMC)方法，建立系統的基本理論架構。以往是用 PI 補償器(未加入模糊控制器)進行掃描探針系統之設計，對力致動器的磁滯效應，有些改善效果。本研究是運用 PID 模糊控制器做為補償器，進行設計，發現結果比用傳統 PI 補償器所提出的方法，還要好，這是一個新的發現。 （英文）This research is to integrate PID type fuzzy controller with the Dynamic Sliding Mode Control (DSMC) to make the system more robust to the dead-band as well as the hysteresis effects of the force actuator. Comparisons with a previous design with PI compensator are also made. This method is more robust than PI compensator. In addition, this idea has been verified by practical implementation of a surface profiler to reduce the hysteresis effect of the force actuator.		
產業別	機械、半導體及光電等產業。		
技術/產品應用範圍	機械、半導體及光電等產業工件，精密控制及量測之掃描探針儀，輪廓儀		
技術移轉可行性及預期效益	機械、半導體及光電等產業，都會對工件，進行精密量測，所以對掃描探針儀及輪廓儀的控制技術，非常殷切，本技術可提供其參考運用，及進行技術移轉。		

註：**本項研發成果若尚未申請專利，請勿揭露可申請專利之主要內容。**

附件四

國科會補助專題研究計畫項下出席國際學術會議心得報告

日期：99 年 1 月 18 日

計畫編號	NSC 97－2221－E－216－013－MY2		
計畫名稱	整合類神經網路及動態滑順模糊控制之可調接觸力垂直探針輪廓儀設計		
出國人員姓名	林君明	服務機構及職稱	中華大學 通訊系 教授
會議時間	99 年 1 月 3 日至 99 年 1 月 8 日	會議地點	香港城市大學
會議名稱	（中文）第 3 屆國際電子電機工程師協會奈米電子研討會 （英文） The IEEE International NanoElectronics Conference (IEEE INEC 2010)		
發表論文題目	（中文）以 RFID 標籤技術為主之微陣列生物探針感測與監控系統整合設計 （英文） Bio-Sensing and Monitor System Design with Micro Array Probes on an Active RFID Tag		

一、參加會議經過

此次論文招募投稿，被接受口頭報告總共有 503 篇文章，海報發表則為 408 篇，總共事 911 篇。而參加的國家多達35個，由此可見此會議之規模，及受國際重視的程度。相關論文將收錄於 IEEE Xplore 及 Engineering Index (EI) 網站，由此可見此會議的重要性。(The extended abstracts of all paid/registered papers will be included in the IEEE Xplore database and Engineering Index (EI)).

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1. Jium-Ming Lin, Po-Wei Lin, and Li-Chern Pan, “Microarray Bioprobe Device Integrated with a Semiconductor Amplifier Having Bottom-Gate Thin Film Transistors,” 美國專利(2008 年 1 月 25 號提出申請，申請號為：US 2008/0297135 A1)。

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圖 1　林君明教授發表論文時之現場情況(1)

圖 2　林君明教授發表論文時之現場情況(2)

二、與會心得

大會第一及第二天早上9點，即再城市大學的演講廳，揭開一天的序幕，9點45分至10點50分，進行當天研討會的兩場專題演講(Plenary Session)，相關議題及內容都非常精采。11點15分至12點15分，開始進行每天的研討會，分10個會場同時進行，場地佈置、資訊取得，及寬廣舒適性都是一流，這是大會非常成功的地方，有此可見香港人辦活動的魄力，值得我們學習。下午也有討論會為，時間是2點至6點30分。我對生醫信號量測及感測器設計有興趣，所以就參加這方面的研討會場次，令人收穫頗多。

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四、建議

出國參加國際會議，的確可以磨鍊一下發表文章的技巧，及吸收別人寶貴的經驗，發掘一些新的研究靈感與題目，所以是非常值得鼓勵的事。而平常自己也要充實英文的能力，屆時才會有更大的收穫。這次有機會進行口頭報告，實在是一次很好磨鍊英文及組織能力的機會。因為事先要先練習所要宣讀會議的論文，找出一些可以討論的題目，這樣在會議中，就可以從容的回答問題，這樣聽眾及報告人都會有更大的收穫，而場面也不會顯得冷清。還好終於圓滿結束，而收穫最多的，其實就是自己。

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六、其他

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日期：99 年 1 月 18 日

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Outline
- (1) Introduction
- (2) Bio-Probes & Amp. Design
- (3) Device Fabrication Steps
- (4) Micro-array Bioprobe Module
- (5) Test & Discussions
- (6) Conclusions

圖 1　林君明教授發表論文時之現場情況(1)

1. Introduction (1)
- This paper integrates micro array bio-probes and thin-film-transistor (TFT) amplifier on a flexible substrate.
- The signal-to-noise ratio and impendence matching problems can be improved.
- The module can be disposed relying on the profile of the living body's portion.

Chung-Hua University

圖 2　林君明教授發表論文時之現場情況(2)

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國科會補助計畫衍生研發成果推廣資料表

日期:2010/12/17

國科會補助計畫	計畫名稱：整合類神經網路及動態滑順模糊控制之可調接觸力垂直探針輪廓儀設計		
	計畫主持人：林君明		
	計畫編號：97-2221-E-216-013-MY2　　學門領域：精密動態控制		
研發成果名稱	（中文）整合類神經網路及動態滑順模糊控制之可調接觸力垂直探針輪廓儀設計		
	（英文）Scanning Probe Microscope Design for Voice Coil Force Actuator with Fuzzy and Dynamic Sliding Mode Controller		
成果歸屬機構	中華大學	發明人（創作人）	林君明
技術說明	（中文）目前以音圈(Voice Coil)或是電磁裝置(Electromagnetic Device)，作爲力致動器(Force Actuator)的趨勢，有快速增加的現象，這是因爲它很便宜，且很容易驅動使用的緣故。但是這種音圈力致動器或電磁裝置，有很嚴重的非線性效應，例如死帶區(Dead Band)，及磁滯效應(Hysteresis Effect)。傳統設計這種非線性系統，是在工作點(Operating Point)的附近，將系統動態方程式進行線性化，再利用各種線性控制方法，進行控制器的設計。但是當系統參數有變化(Parameter Variation)，或是有負載干擾(Load Disturbance) ，或是有死帶區，或是有磁滯效應時，這些預先設計好(增益及補償器皆爲固定式)的控制器，就不一定能使系統維持良好的反應，可能誤差會加大，甚至產生不穩定的現象，所以必須要找一個更有效的方法。本研究之可調接觸力輪廓儀設計，是以模糊控制理論，結合動態滑動模式控制(Dynamic Sliding Mode Control, DSMC)方法，建立系統的基本理論架構。以往是用 PI補償器(未加入模糊控制器)進行掃描探針系統之設計，對力致動器的磁滯效應，有些改善效果。本研究是運用PID模糊控制器做爲補償器，進行設計，發現結果比用傳統PI補償器所提出的方法，還要好，這是一個新的發現。		
	（英文）This research is to integrate PID type fuzzy controller with the Dynamic Sliding Mode Control (DSMC) to make the system more robust to the dead-band as well as the hysteresis effects of the force actuator. Comparisons with a previous design with PI compensator are also made. This method is more robust than PI compensator. In addition, this idea has been verified by practical implementation of a surface profiler to reduce the hysteresis effect of the force actuator.		
產業別	電機及電子機械器材業		
技術/產品應用範圍	機械、半導體及光電等產業工件，精密控制及量測之掃描探針儀，輪廓儀		
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註：本項研發成果若尚未申請專利，請勿揭露可申請專利之主要內容。

97 年度專題研究計畫研究成果彙整表

計畫主持人：林君明　**計畫編號：**97-2221-E-216-013-MY2

計畫名稱：整合類神經網路及動態滑順模糊控制之可調接觸力垂直探針輪廓儀設計

成果項目			量化			單位	備註（質化說明：如數個計畫共同成果、成果列為該期刊之封面故事...等）
			實際已達成數（被接受或已發表）	預期總達成數(含實際已達成數)	本計畫實際貢獻百分比		
國內	論文著作	期刊論文	0	0	100%	篇	
		研究報告/技術報告	0	0	100%		
		研討會論文	0	0	100%		
		專書	0	0	100%		
	專利	申請中件數	0	0	100%	件	
		已獲得件數	0	0	100%		
	技術移轉	件數	0	0	100%	件	
		權利金	0	0	100%	千元	
	參與計畫人力（本國籍）	碩士生	0	0	100%	人次	
		博士生	0	0	100%		
		博士後研究員	0	0	100%		
		專任助理	0	0	100%		
國外	論文著作	期刊論文	0	0	100%	篇	
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		研討會論文	0	0	100%		
		專書	0	0	100%	章/本	
	專利	申請中件數	0	0	100%	件	
		已獲得件數	0	0	100%		
	技術移轉	件數	0	0	100%	件	
		權利金	0	0	100%	千元	
	參與計畫人力（外國籍）	碩士生	0	0	100%	人次	
		博士生	0	0	100%		
		博士後研究員	0	0	100%		
		專任助理	0	0	100%		

其他成果 (無法以量化表達之成果如辦理學術活動、獲得獎項、重要國際合作、研究成果國際影響力及其他協助產業技術發展之具體效益事項等，請以文字敘述填列。)	本計畫研究成果，已被下列國際期刊接受 (1). Jium-Ming Lin and Po-Kuang Chang, ’Applying Intelligent Fuzzy Control to Reduce Hysteresis Effect of Force Actuator in a SPM,’ WSEAS Transactions on Systems and Control, Vol.4, Issue 7, pp. 271-285, July 2009. (EI) (2). Po-Kuang Chang and Jium-Ming Lin, ’Intelligent Fuzzy Control of a Scanning Probe Microscope System Design,’ ICIC Express Letters, Vol. 3, No. 4(A), pp. 951- 956, December 2009. (EI) (3). Jium-Ming Lin and Po-Kuang Chang, ’Eliminating Hysteresis Effect of Force Actuator in a SPM,’ WSEAS Transactions on Systems and Control, Vol. 5, Issue 1, pp. 1-15, January, 2010. (EI) (4). Jium-Ming Lin and Po-Kuang Chang, ’Integration both PI and PD Type Fuzzy Controllers for a Scanning Probe Microscope System Design,’ WSEAS Transactions on Systems and Control, Volume 5, Issue 6, pp. 484-497, June 2010 (EI). (5). Po-Kuang Chang and Jium-Ming Lin, ’Intelligent Fuzzy PID Controller Design of a Scanning Probe Microscope System,’ Accept for publication at International Journal of Electronics, Electrical and Communication Engineering (IJEECE), 2010.

🟥	成果項目	量化	名稱或內容性質簡述
科教處計畫加填項目	測驗工具(含質性與量性)	0	
	課程/模組	0	
	電腦及網路系統或工具	0	
	教材	0	
	舉辦之活動/競賽	0	
	研討會/工作坊	0	
	電子報、網站	0	
	計畫成果推廣之參與（閱聽）人數	0	

國科會補助專題研究計畫成果報告自評表

請就研究內容與原計畫相符程度、達成預期目標情況、研究成果之學術或應用價值（簡要敘述成果所代表之意義、價值、影響或進一步發展之可能性）、是否適合在學術期刊發表或申請專利、主要發現或其他有關價值等，作一綜合評估。

1. 請就研究內容與原計畫相符程度、達成預期目標情況作一綜合評估

■達成目標

□未達成目標（請說明，以 100 字為限）

□實驗失敗

□因故實驗中斷

□其他原因

說明：

2. 研究成果在學術期刊發表或申請專利等情形：

論文：■已發表 □未發表之文稿 □撰寫中 □無

專利：□已獲得 □申請中 ■無

技轉：□已技轉 □洽談中 ■無

其他：（以 100 字為限）

Applying Intelligent Fuzzy Control to Reduce Hysteresis Effect of Force Actuator in a SPM,

3. 請依學術成就、技術創新、社會影響等方面，評估研究成果之學術或應用價值（簡要敘述成果所代表之意義、價值、影響或進一步發展之可能性）（以 500 字為限）

本研究之可調接觸力輪廓儀設計，是以模糊控制理論，結合動態滑動模式控制(Dynamic Sliding Mode Control, DSMC)方法，建立系統的基本理論架構。以往是用 PI 補償器(未加入模糊控制器)進行掃描探針系統之設計，對力致動器的磁滯效應，有些改善效果。本研究是運用 PID 模糊控制器做為補償器，進行設計，發現結果比用傳統 PI 補償器所提出的方法，還要好，這是一個新的發現。