行政院國家科學委員會專題研究計畫 成果報告

具有內迴路阻尼調整之可控制接觸力掃描探針顯微系統設計(II)

研究成果報告(精簡版)

計 畫 類 別 ：個別型
計 畫 編 號 ：NSC 96-2221-E-216-029-
執 行 期 間 ：96 年 08 月 01 日至 97 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 ：本計畫可公開查詢

中 華 民 國 97 年 10 月 02 日

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

具有內迴路阻尼調整之可控制接觸力掃描探針顯微系統設計(II)

計畫類別：■ 個別型計畫　　□ 整合型計畫
計畫編號：NSC 96－2221－E －216 －029－
執行期間：　96 年　8 月　1 日至　97 年　7 月　31 日

計畫主持人：林君明
共同主持人：
計畫參與人員：　侯忠慶、史廷揆

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

本成果報告包括以下應繳交之附件：
□赴國外出差或研習心得報告一份
□赴大陸地區出差或研習心得報告一份
■出席國際學術會議心得報告及發表之論文各一份
□國際合作研究計畫國外研究報告書一份

處理方式：除產學合作研究計畫、提升產業技術及人才培育研究計畫、列管計畫及下列情形者外，得立即公開查詢
□涉及專利或其他智慧財產權，□一年□二年後可公開查詢

執行單位：中華大學機械工程學系

中　華　民　國　97　年　10　月　1　日

中文摘要

本研究是完成一套「可控制接觸力之掃描探針顯微系統」。此系統主要元件包括：XYZ 移動平台、力致動器、線性可調式差分變壓器(Linear Variable Differential Transformer，LVDT)、荷重計(Load Cell)、垂直鑽石探針頭、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 40 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，並利用 PID 控制器補償，將荷重計的訊號做回授與處理，再將誤差訊號，傳到力致動器，做施力誤差補償。本期研究計畫擬將上述系統加以推廣，並採用線性速度感測器(Linear Velocity Transducer, LVT) ，感測垂直探針的上下移動速度作為迴授，以改善內迴路的阻尼及反應速度。經過初步模擬發現效果不錯，的確有改善力致動器磁滯效應及反應速度的功能。

關鍵詞: 線性速度感測器，線性差分變壓器，荷重計

英文摘要

This research upgraded the previous work of a contact force controlled scanning probe microscopy system design, the main part of this system are as: XYZ-stage, force actuator and driving circuit, Linear Variable Differential Transformer(LVDT), Linear Velocity Transducer(LVT), load cell, diamond probe, data acquisition board, and operating system programming. By using PID controller, the contact-force of the probe is feedback for monitoring the force actuator to meet the desired contact-force between the probe and the object as well as to minimize the hysteresis effect of the force actuator. Finally, the profile of the object surface is displayed on a 3D graph. The accuracy of the system is 1 μm.

This research used a Linear Velocity Transducer (LVT) to detect the vertical moving velocity of the stylus probe for the force actuator inner-loop damping and transient behavior control. This improvement has been verified by MATLAB simulation to reduce the hysteresis effect and the transient response of the force actuator.

The other effects that will degrade the performance of measurement accuracy are probe tip, Linear Variable Differential Transformer (LVDT), and load cell. In the previous work, the probe tip is with radius 2 μm and angle 60 degrees. The accuracy of LVDT is 1μm. The measurement resolution of load cell is 40 mg. To improve the system performance of the proposed surface profiler this project is going to purchase the probe tip with radius 100 nm and angle 10 degrees. The resolution of load cell is 5 mg, and the up-graded LVDT as well as the circuit layout artwork.

Keywords: Linear Velocity Transducer (LVT), Linear Variable Differential Transformer (LVDT), Load Cell

前言

由於我國目前正大力推動兩兆雙星產業，所以要投入大量資金，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。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。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。

研究目的

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。由計畫主持人前一部份五年內的研究經歷可知，以往本研究已經完成一套精度可達 1μm 的接觸式掃描探針顯微系統，如圖 1。本計畫的目的是將量測的精度，提升一個數量級。

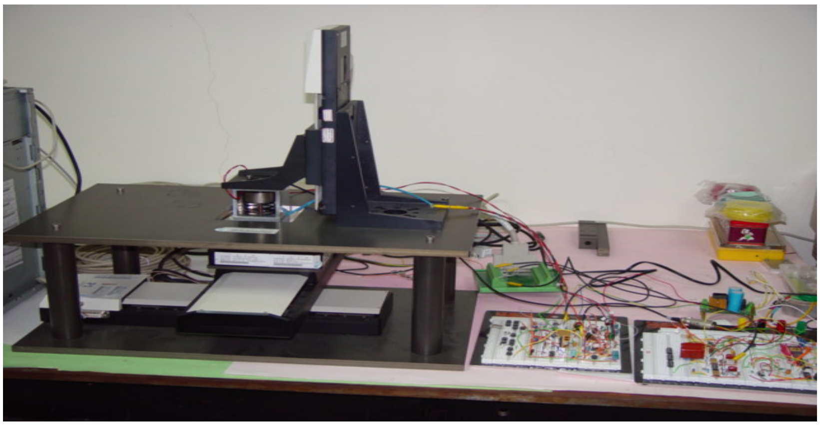


圖 1 可控制接觸力之掃描探針顯微系統

以往研發之系統主要元件包括：XYZ 移動平台、力致動器、線性可調式差分變壓器(Linear Variable Differential Transformer，LVDT)、荷重計(Load Cell)、垂直鑽石探針頭、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 40 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，並利用 PID 控制器補償，將荷重計的訊號做回授與處理，再將誤差訊號，傳到力致動器，做施力誤差補償。系統硬體架構連結及 MATLAB 模擬方塊，如圖 2 及 3。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，如圖 4。由此圖可知系統的性能會受到力致動器遲滯效應(Hysteresis Effect)的影響，如圖 5。

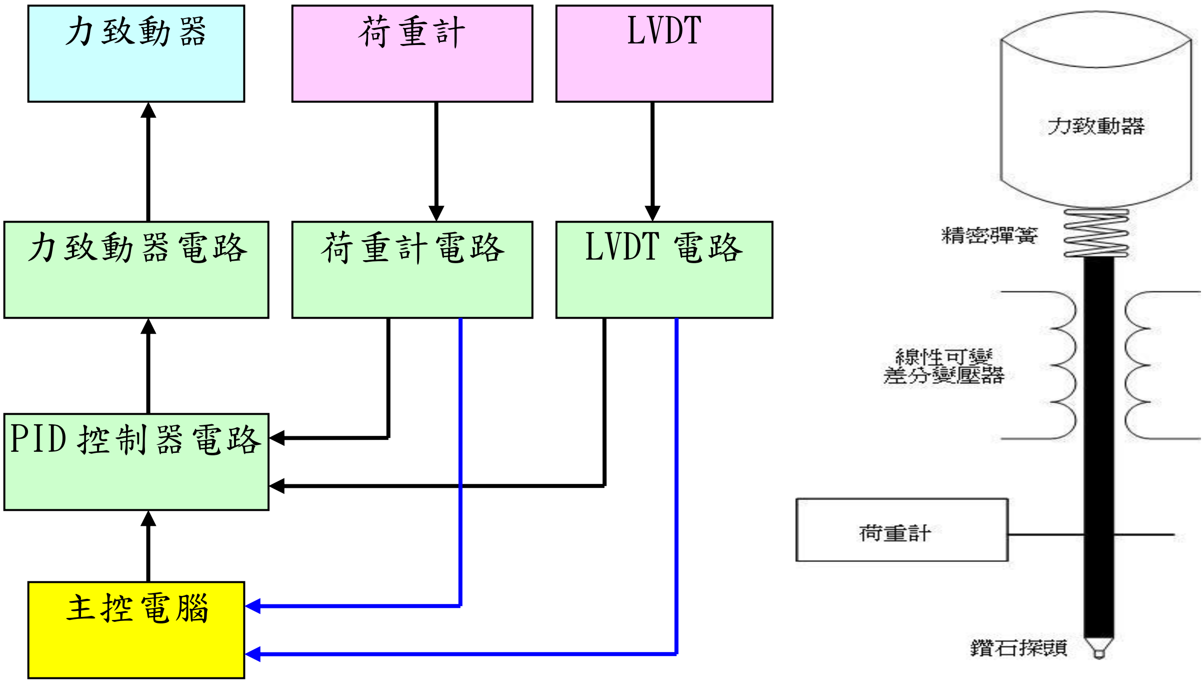


圖 2 可控制接觸力之掃描探針顯微系統(a)架構連結方塊及(b)硬體圖

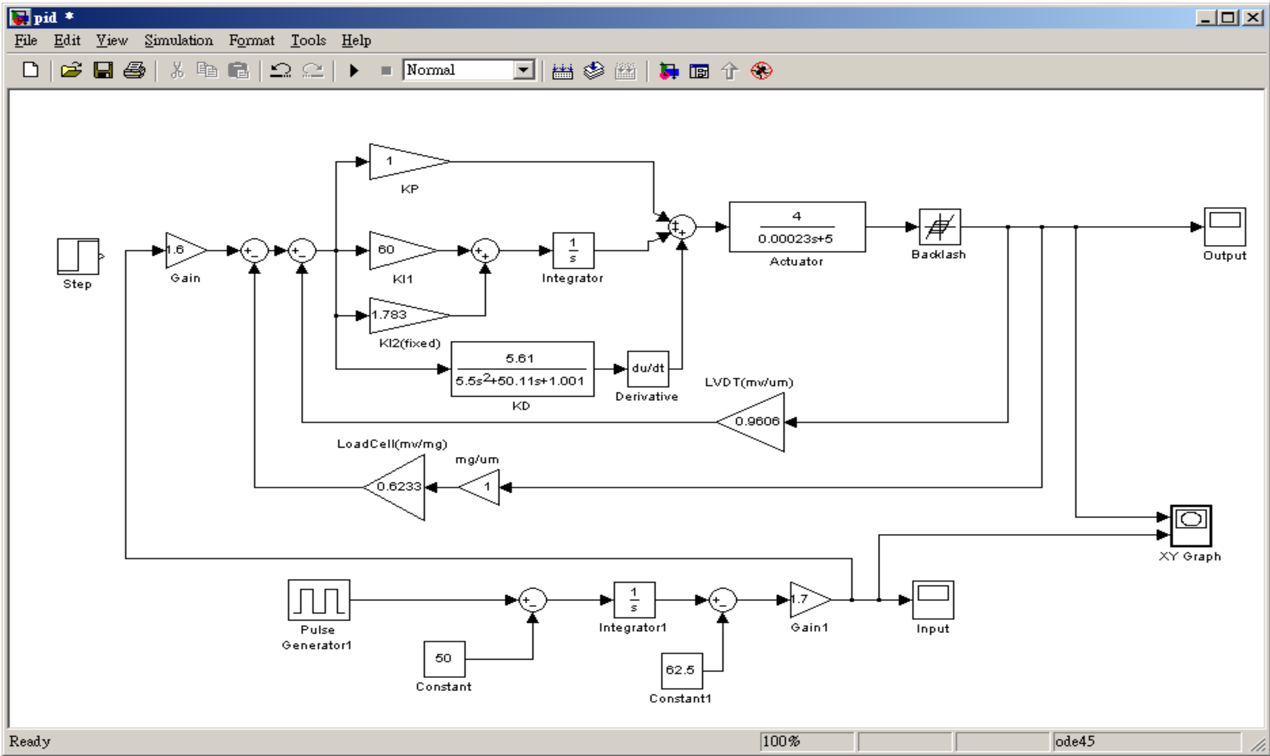


圖 3 MATLAB 系統模擬方塊圖

圖 4 印刷電路板表面量測高低分佈的情形

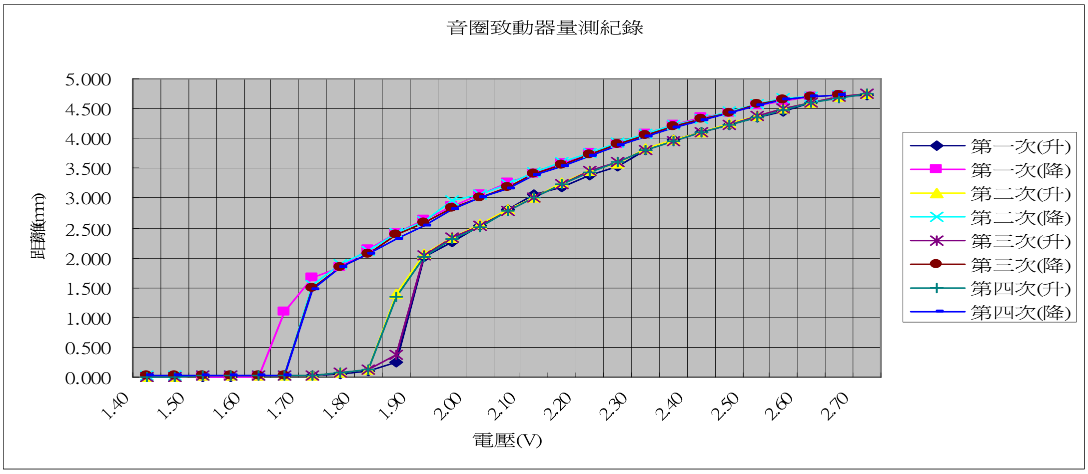


圖 5 力致動器特性(磁滯效應)曲線量測圖

後來解決的方法是在前向迴路中，加入 PID 控制器，雖可降低其影響，但是微分控制器會造成雜訊放大效應，所以後來沒有採用，如圖 7-9 所示是只有在前向迴路中，用到 PI 控制器的力致動器(a)輸入三角波,(b)輸出三角波,及(c)磁滯效應曲線圖，當積分器的增益逐漸增加，超過某一數值時，此種補償方式對於力致動器磁滯效應的改善，趨於一極限。而另一方面，當積分器的增益太高時，系統反應變差，量測結果比較容易震盪而不穩定，為一項缺點。

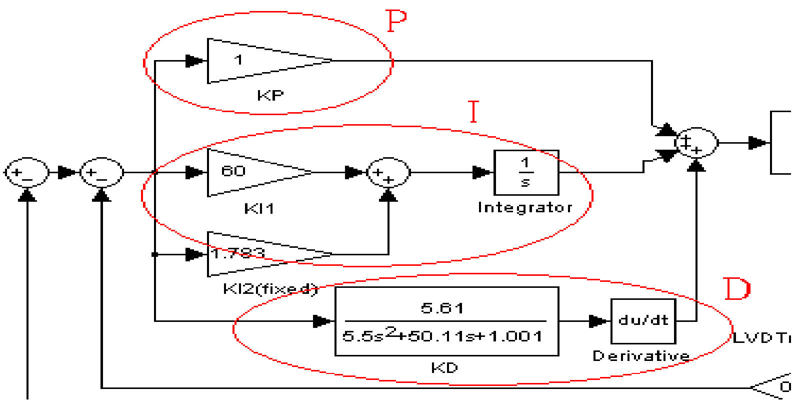


圖 6 PID 控制器方塊圖

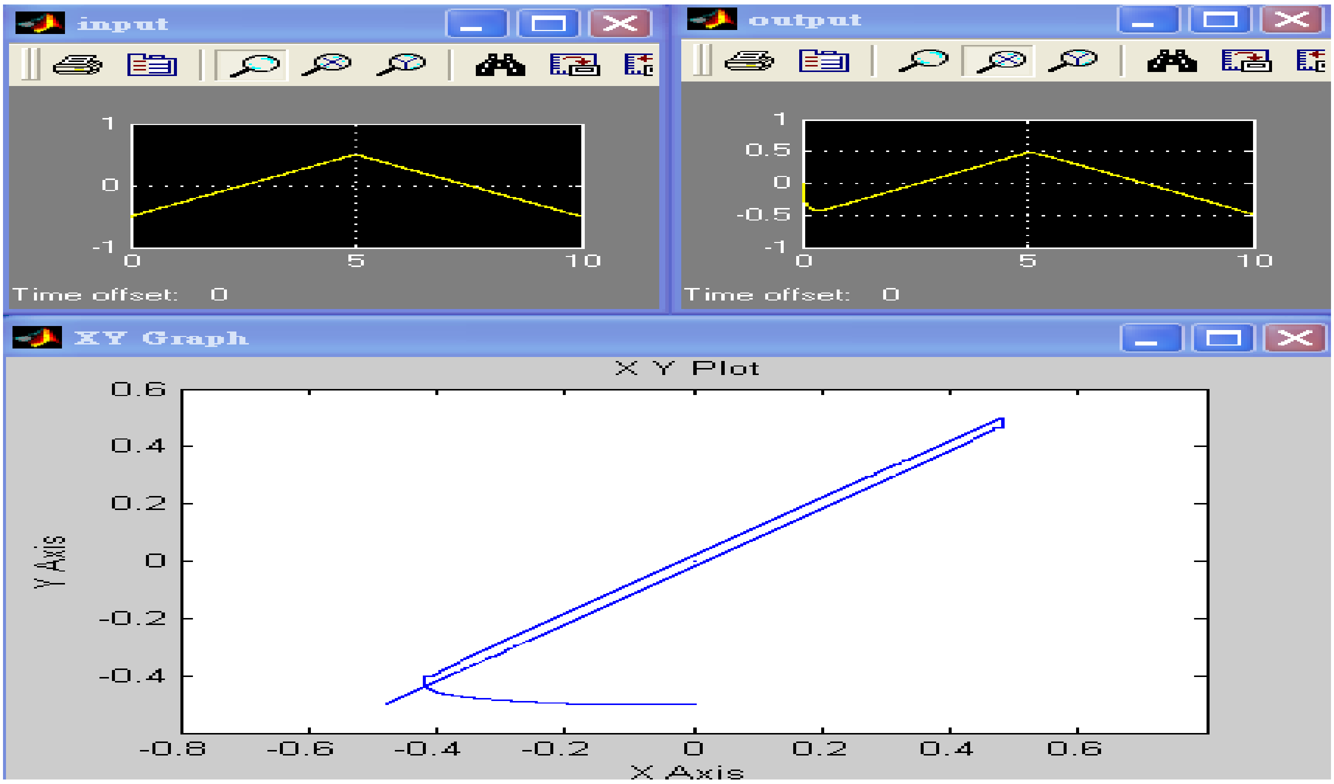


圖 7 P = 0.5，I = 10 之力致動器(a)輸入三角波,(b)輸出三角波,及(c)磁滯效應曲線圖

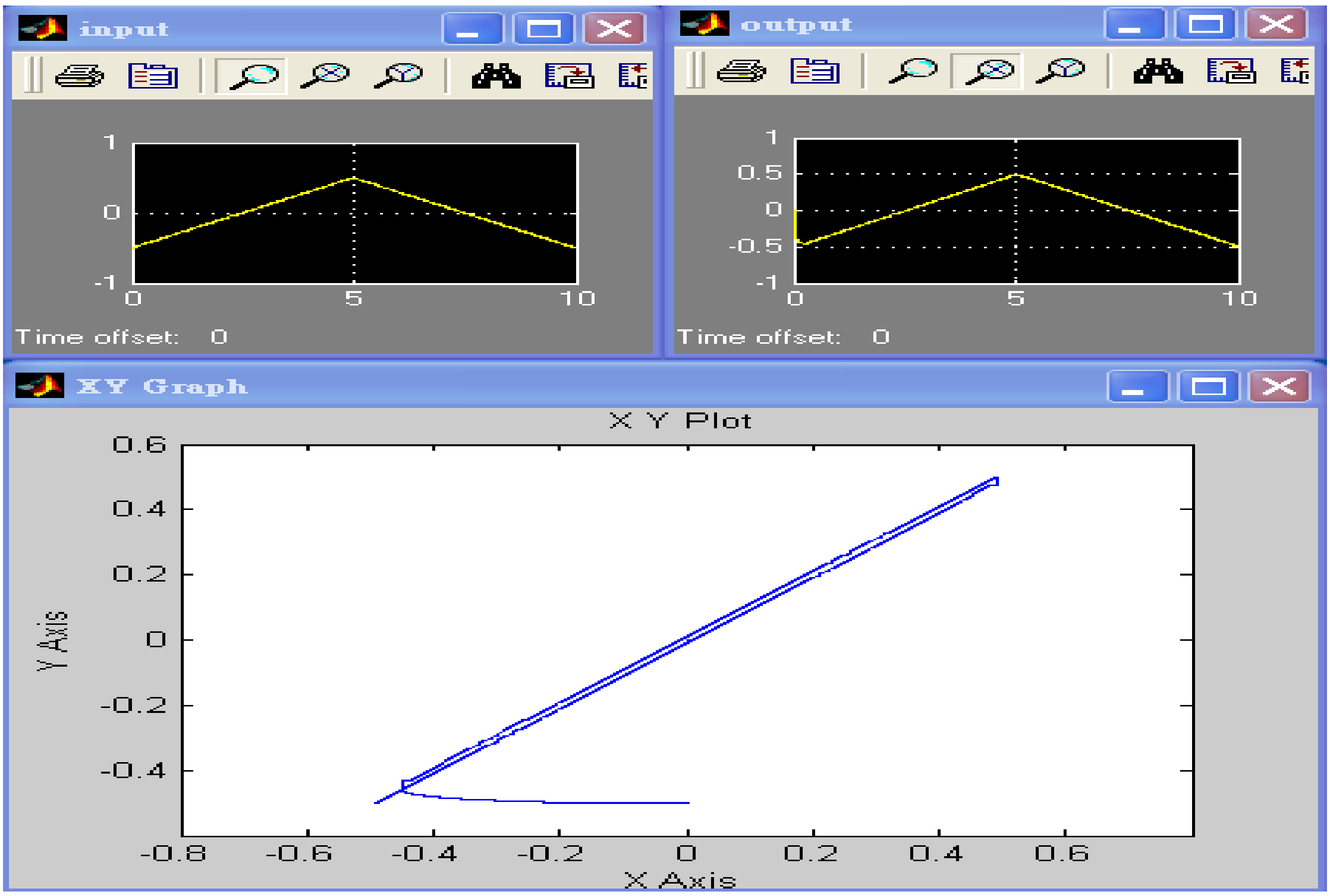


圖 8 P = 0.5，I = 20 之力致動器(a)輸入三角波,(b)輸出三角波,及(c)磁滯效應曲線圖

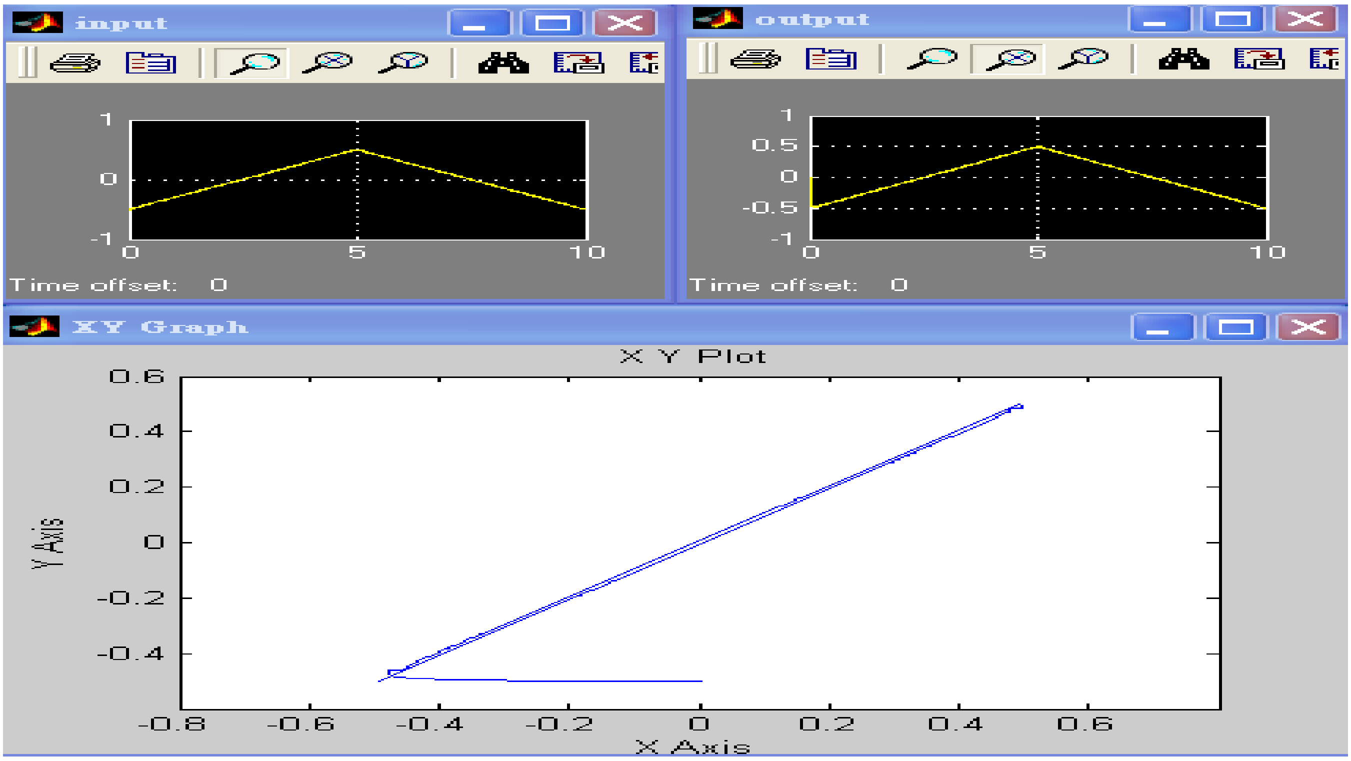


圖 9 P = 0.5，I = 50.5 之力致動器(a)輸入三角波,(b)輸出三角波,及(c)磁滯效應曲線圖

研究方法

本研究計畫是採用線性速度感測器(Linear Velocity Transducer, LVT) ，感測垂直探針的上下移動速度作為迴授，以改善力致動器內迴路的阻尼，及反應速度(Inner-Loop Damping and Transient Response)，如圖 10。經過模擬發現效果不錯，的確有改善力致動器磁滯效應的功能，如圖 11(內迴路補償器只有 P=1 之結果) ，及圖 12(內迴路補償器只有 P=1, I=200 之結果) 。比較圖 12 及圖 9，可見這種內迴路採用速度感測器作為迴授，不僅可以改善內迴路的阻尼及反應速度，也可以改善力致動器磁滯效應。

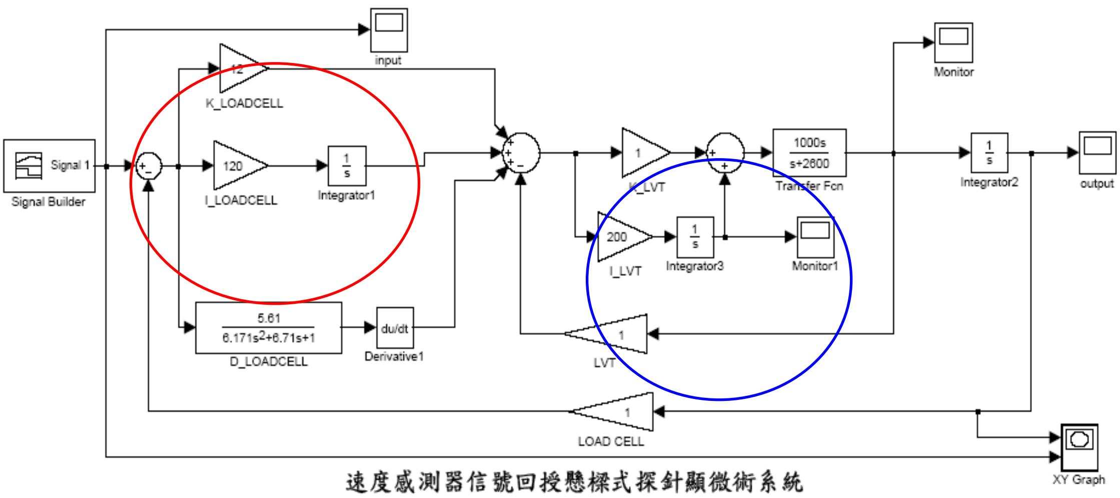


圖 10 採用線性速度感測器(LVT)作為回授，改善內迴路的阻尼及反應速度之系統方塊圖

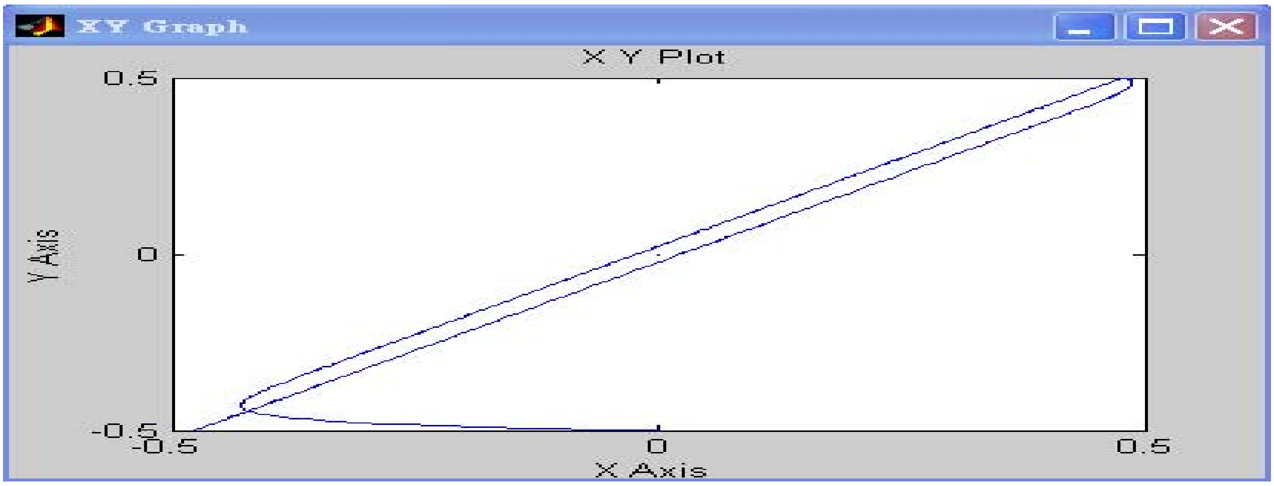


圖 11 內迴路補償器只有 P=1 之力致動器磁滯效應曲線圖

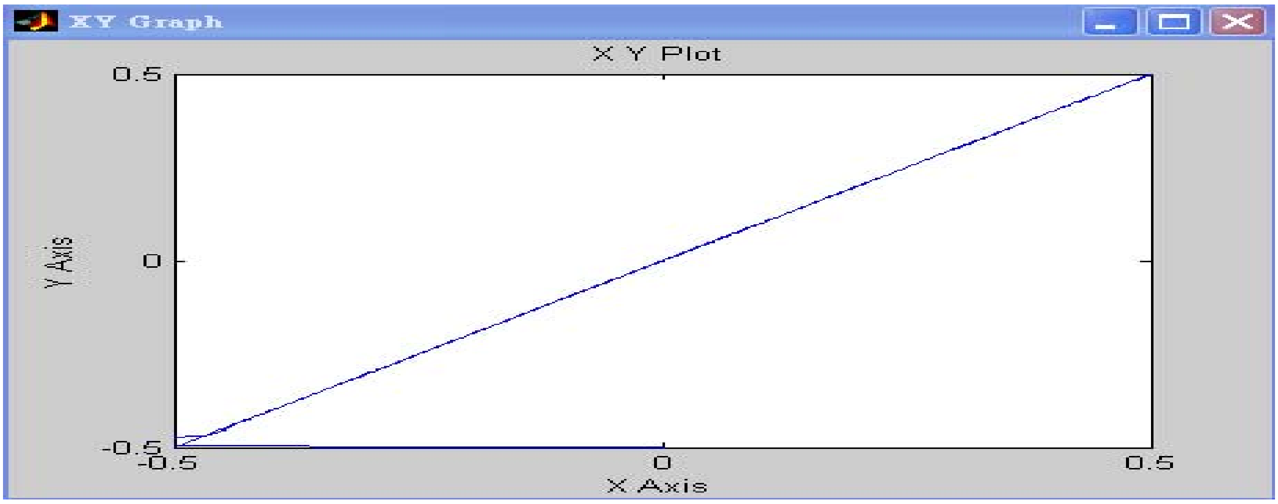


圖 12 內迴路補償器只有 P=1, I=200 之力致動器磁滯效應曲線圖

經過以上的模擬分析，我們確認此種研究構想的可行性之後，即可進行系統硬體的採購，如線性速度感測器(LVT) ，與補償器電路設計製作，如下列圖 13 及 14。

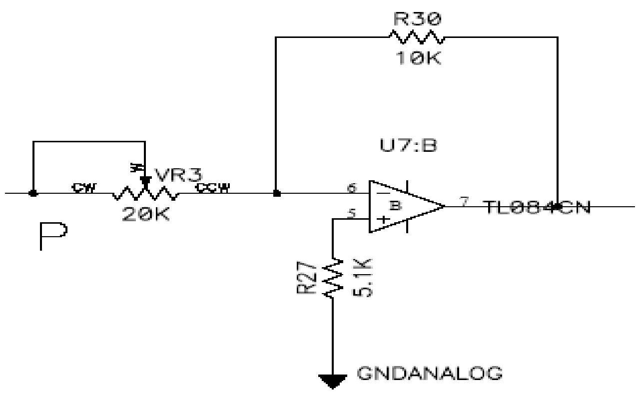
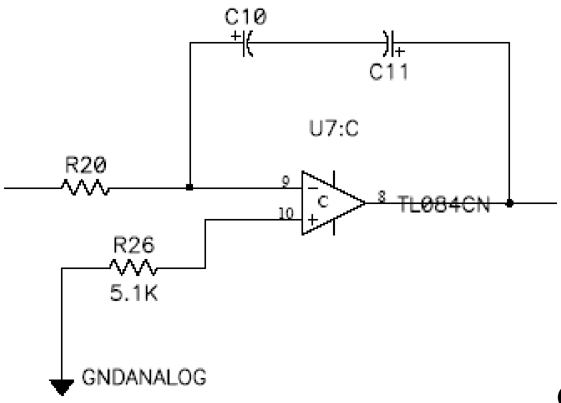


圖 13 PI 控制的 P 參數控制與實際電路



$$G_C(s) = -\frac{1/R_{20}C}{S}$$

圖 14　PI 控制的積分參數控制與實際電路

結果與討論

另一些會影響本系統性能的因素是探針頭，線性差分變壓器(LVDT) ，及荷重計(Load Cell) 。以往是使用尖端半徑為 2 μm、張角 60 度的鑽石探頭。而線性差分變壓器的精度為 1μm。荷重計的解析度為 40 毫克。若本系統在量測精度上要再提高，則需另外購置經過雷射加工，尖端半徑為 100 奈米，張角為 10 度的探針頭。所以只要系統後端信號處理技術再提高，或選用靈敏度為 5 毫克的荷重計，及精度更高的線性差分變壓器，則可以獲得更高精度的待測物表面資訊。

參考文獻

[1] P.A. Rasmussen, J. Thaysen, S.Bouwstra, and A. Boisen, Modular Design of AFM Probe with Sputtered Silicon Tip.

[2] Po-Lun Cheng and Wensyang Hsu, Design and Fabrication of a Strain-Type Atomic Force Microscopy.

[3] Binnig G., Rohrer H., Gerber C. and Weibel E, “Surface studies by scanning tunneling microscope,” *Phys. Rev. Lett.* Vol. 49, 1982, pp. 57-61.

[4] H. Watanabe, T. Baba, and M. Ichikawa, 1999, *J. Appl. Phys.* Vol. 85, p.6704.

[5] E. S. Daniel, J. T. Jones, O. J. Marsh, and T. C. McGill 1997, J. Vac. Sci. Technol. B, 15, 1089

[6] Binning G., Quate C. F., and Gerber C., “Atomic Force Microscope,” Phys. Rev. Lett. Vol. 56, No. 9, 1986, pp. 930-933.

[7] S. J. O`Shea, R. M. Murrell, and M. E. Welland 1995, J. Vac. Sci. Technol. B, 13 1945

[8] C. C. Williams, H. K. Wickramasinghe, “Scanning Thermal Profiler,” Appl. Phys. Lett. Vol. 49, 1986, pp.1587-1589.

成果發表於下：

Proceedings of 2007 CACS International Automatic Control Conference
National Chung Hsing University, Taichung, Taiwan, Nov. 9-11, 2007

Scanning Probe Microscope System Design with Linear Velocity Transducer for Feedback Compensation

Jium-Ming LIN
School of Mechanical Engineering and Astronautics, Chung-Hua University
Hsin-Chu, Taiwan, ROC
e-mail: jmlin@chu.edu.tw

Jiea-Chie LIN
School of Mechanical Engineering and Astronautics, Chung-Hua University
Hsin-Chu, Taiwan, ROC
e-mail: m09308037@chu.edu.tw

***Abstract*—This research is to use Linear Velocity Transducer (LVT) to detect the vertical velocity of the stylus probe for the inner-loop damping and transient control of a force actuator. This improvement has been verified by MATLAB simulation and practical implementation of a surface profiler to reduce the hysteresis effect of the force actuator.**

***Keywords* —LVT, LVDT, Load cell, Surface profiler.**

I. INTRODUCTION

The Scanning Probe Microscopy (SPM) has been developed rapidly in the last two decade [1]. 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 of past research [2], a balance with stylus probe, force actuator, LVDT (Linear Variable Differential Transformer), 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.

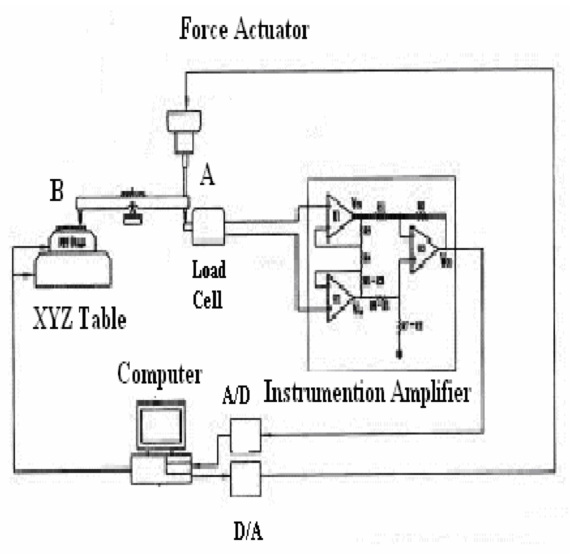


Fig.1. The contact force-controlled SPM system.

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

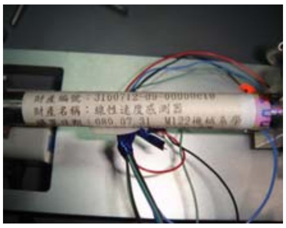


Fig. 2. The LVT.

Fig. 3. The stylus probe.

Fig.4a. The voice coil.

Fig. 4b. The LVDT.

Fig. 5a.The load cell.

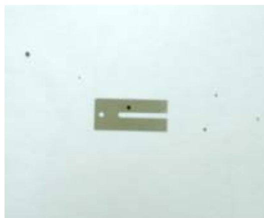


Fig. 5b.The leaf spring.

In addition to the XYZ-stages a piezo-stage in Fig. 6 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.This improvement has been verified by MATLAB simulation and practical implementation of a surface profiler to reduce the hysteresis effect of the force actuator.

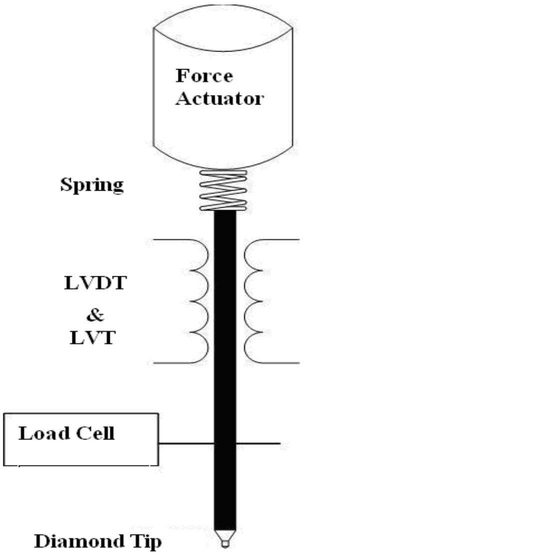


Fig. 5c. The installation structure of load cell, voice coil LVT and LVDT.

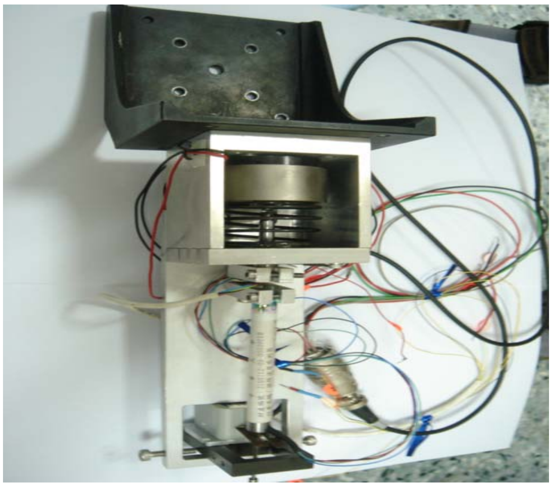


Fig. 5d. Integration of voice coil, LVT & LVDT.

Fig. 6. The piezo-stage and the sample holder.

II. PRINCIPLE OF 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. 7a, 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 a vertical displacement as shown in Fig. 7b.

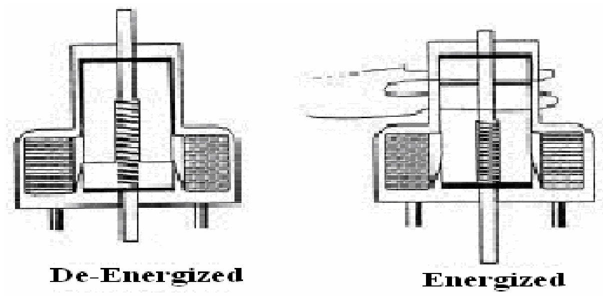


Fig.7a. Force actuator de-energized. Fig.7b. Force actuator energized.

The relationship of the applied voltage and the displacement is shown in Fig. 8. In order to reduce the hysteresis-effect of the force actuator in Fig. 8, 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. 9. A saw tooth-shaped voltage (with peak value =100 mV) as shown in Fig.10, which stands for the displacement command of the force actuator as well as the probe, is applied to the input of the compensated force actuator.

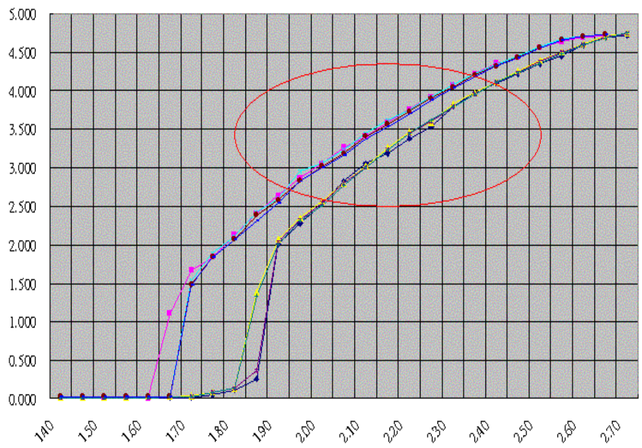


Fig. 8. The relationship of the applied voltage and the displacement of force actuator.

If the gains of the compensator are set as P=1, then the output of LVDT is shown in Fig. 11 by MATLAB simulation. One can see the hysteresis effect still exists as shown in Fig. 12 with output and input on the x and y axes, respectively. After a little while of trial-and-error one has a very good result with P=1 and I=200, respectively, e.g. the output of LVDT is shown in Fig. 13, and the hysteresis effect is almost disappeared as shown in Fig. 14. Finally, the simulation block diagram of the whole system is shown in Fig.9, 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.

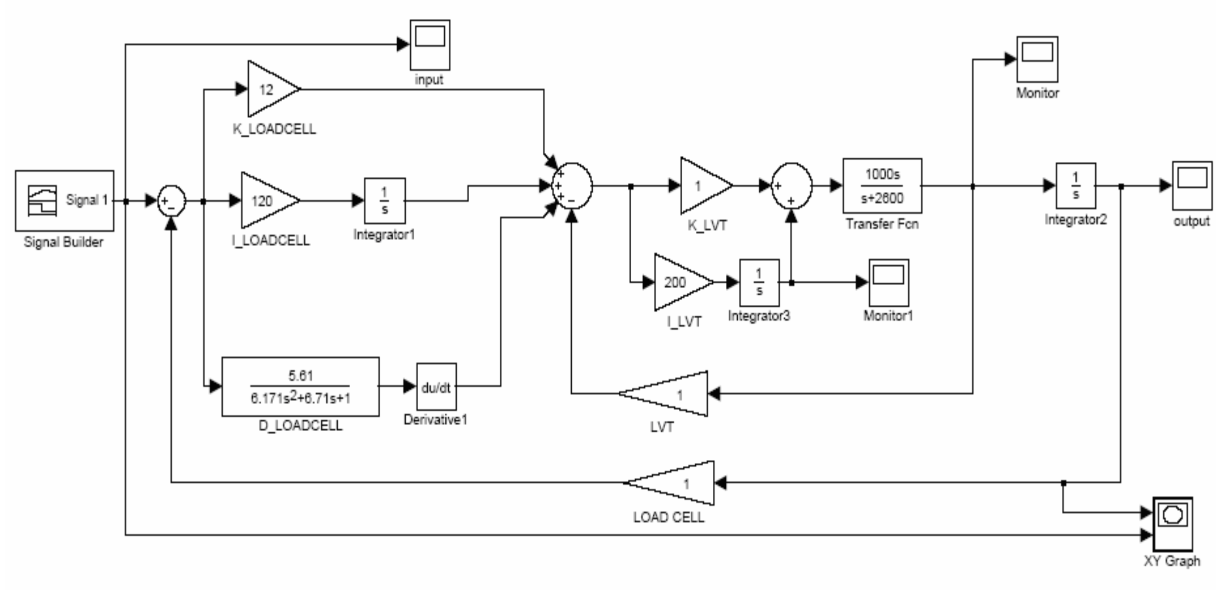


Fig. 9. The design with a PI compensator and a LVT respectively in the forward and feedback paths of force actuator.

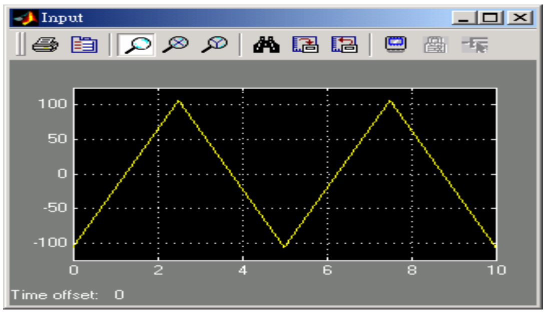


Fig. 10. A saw tooth shaped voltage (displacement command) is applied to the input of the compensated force actuator.

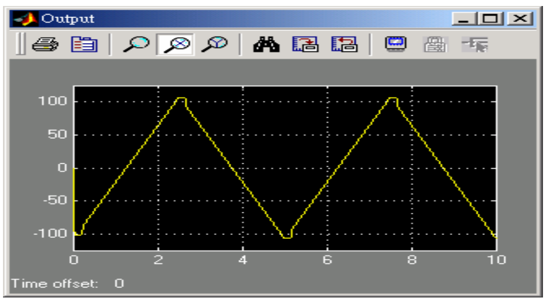


Fig. 11. Output of LVDT shows the hysteresis effect still exists with P=1.

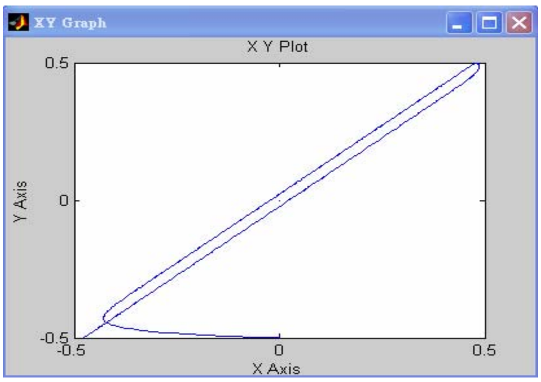


Fig. 12. Hysteresis effect still exists with P=1.

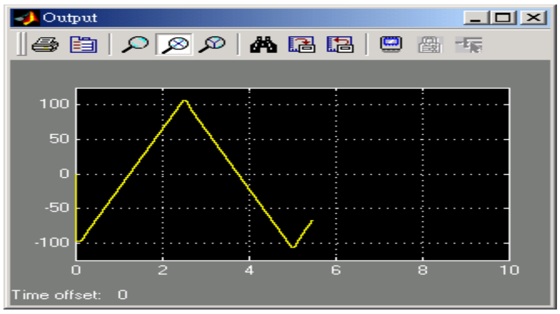


Fig. 13. Output of LVDT shows the hysteresis effect is almost disappeared with P=1 and I=200.

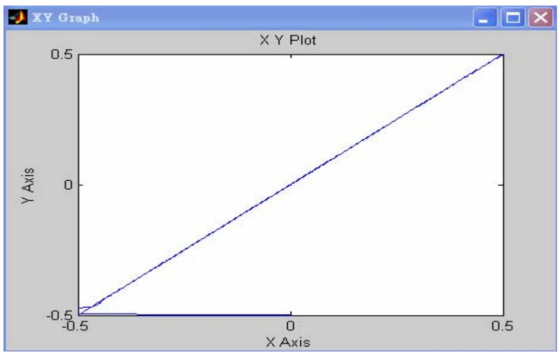


Fig. 14. Hysteresis effect is almost disappeared with P=1 and I=200.

III. TEST RESULTS AND DISCUSSIONS

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. 15. 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.

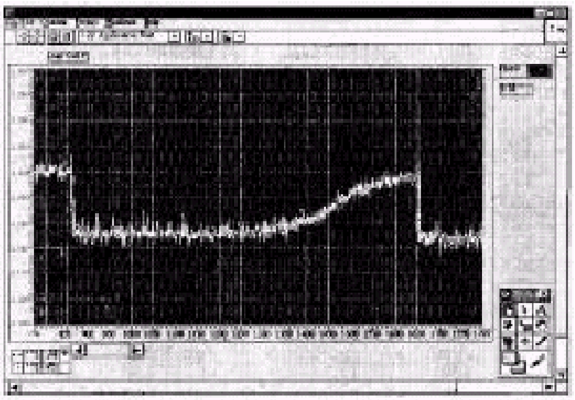


Fig. 15. Output voltage of the load cell is increased for the contact force changing from 0 mg to 40 mg.

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. 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. 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. 16 from LVDT. If one should like to see the top view, the result is shown in Fig. 17.

IV. CONCLUSIONS

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 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) to detect the vertical velocity of the stylus probe for the inner-loop damping and transient control of a force actuator. This improvement has been verified by MATLAB simulation and practical implementation of a surface profiler to reduce the hysteresis effect of the force actuator. Finally, the profile of the object surface is displayed on a 3D graph.

ACKNOWLEDGMENT(S)

This research was supported by National Science Council under the grant of NSC 95-2221-E-216-012.

REFERENCES

[1] G. Neubauer, “Force Microscopy with a Bidirectional Capacitor Sensor,” *Rev. Science Instrument*, vol. 61, pp. 2296-2308, 1990.

[2] Jium-Ming Lin and Jun-Che Lin, “Surface Profiler Design with Multi-Sensor Data Fusion Methods,” *Proceedings of 2005 International Conference on Advance Manufacture*, Nov. 28-Dec. 02, 2005.

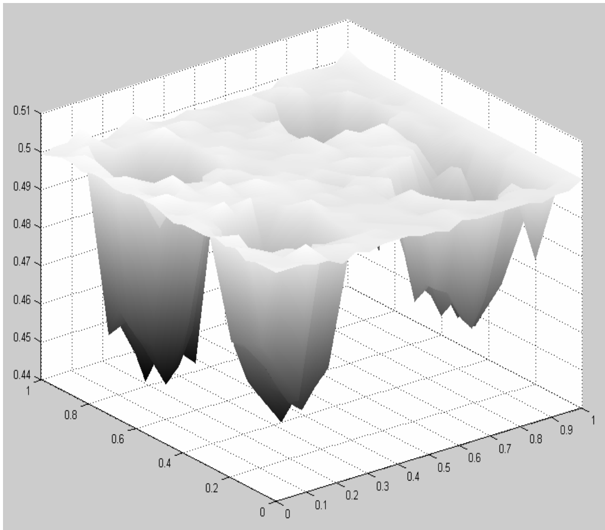


Fig. 16. The surface profile of the sample.

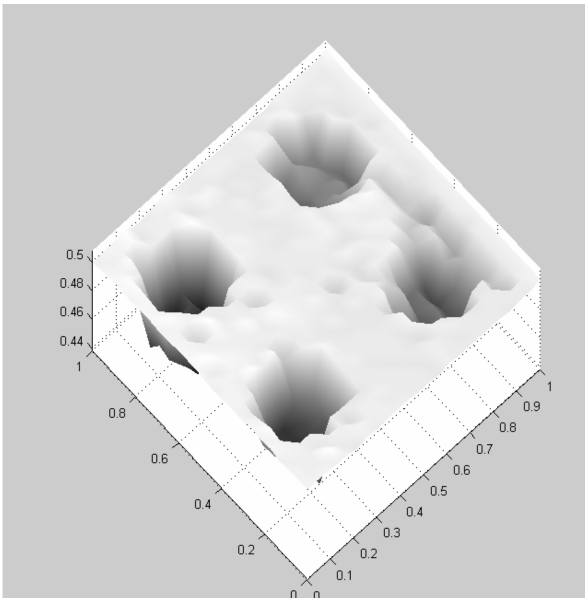


Fig. 17. The top view of the sample.

Scanning probe microscope system design with fuzzy control

Po-Kuang Chang and Jium-Ming Lin

Abstract**—**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 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.

Keywords**—**Scanning Probe Microscope, force actuator, hysteresis effect, fuzzy controller.

I. Introduction

The Scanning Probe Microscopy (SPM) has been developed rapidly in the last two decade [1-12]. 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 of previous research [13], a balance with stylus probe, force actuator, LVDT (Linear Variable Differential Transformer), 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 the probe vertical displacement and velocity. The load cell in Fig. 6 was used to detect the contact force between the probe and sample to be tested. A leaf spring in Fig.7 was applied to integrate the load cell with voice coil, LVT and LVDT module as shown in Figs. 8~9. In addition to the XYZ-stages a piezo-stage in Fig. 10 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.

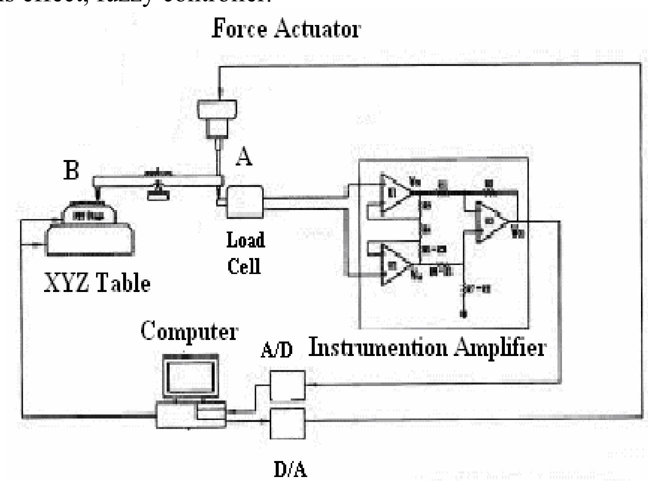


Fig.1 the contact force-controlled SPM system.

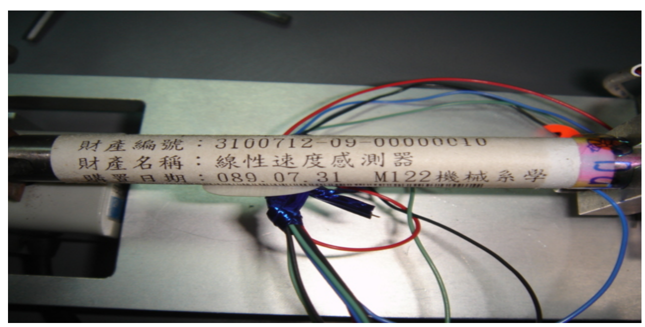


Fig.2 the LVT is to detect the vertical velocity of the stylus probe.

Fig.3 the stylus probe. Fig.4 the voice coil

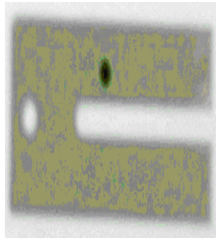


Fig.5 the LVDT. Fig.6 the load cell. Fig.7 the leaf spring.

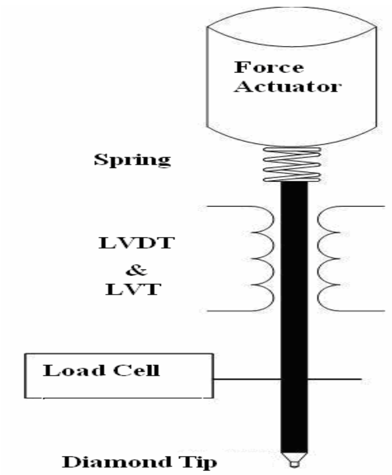


Fig.8 the installation method of load cell, voice coil LVT and LVDT.

Fig.9 the integration module of voice coil, LVT & LVDT.

Fig.10 the piezo-stage and the sample holder.

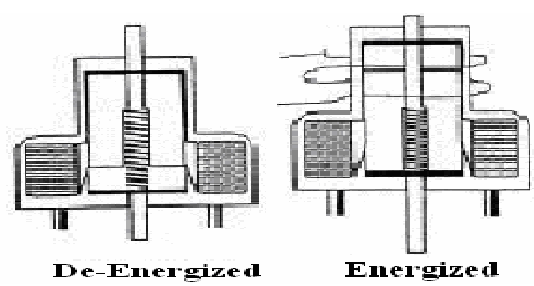
Firstly, this research applied the PI compensator or fuzzy controller for design. both the traditional PI (Proportion and Integration) compensator and the fuzzy control methods for the SPM system design. In addition, the actuator hysteresis effect was taken into consideration. For comparison purpose 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.

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.

II. Principle of 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.11a 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. 11b. The relationship of the applied voltage and the displacement is shown in Fig.12. In order to reduce the hysteresis-effect of the force actuator in Fig.12, 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.13.

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. 14. 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.



(a) (b)

Fig.11 force actuator (a) de-energized. (b) energized.

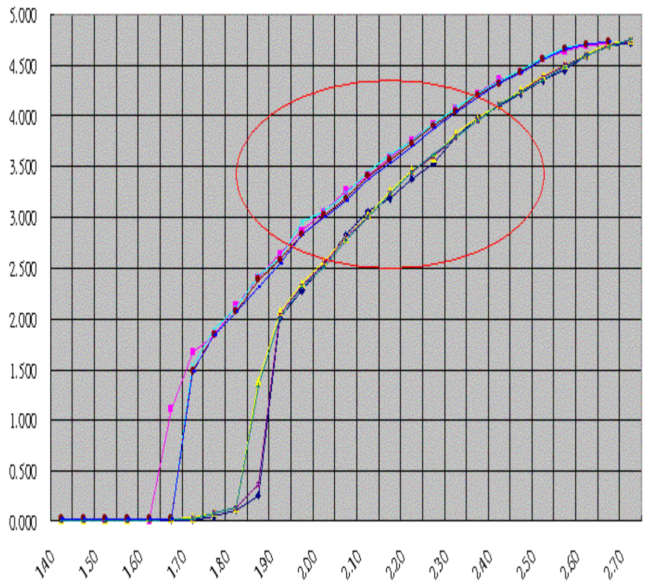


Fig.12 force actuator applied voltage versus displacement.

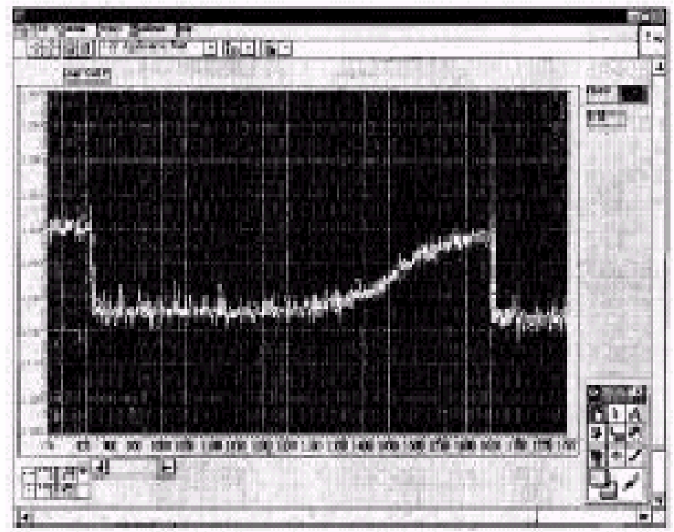


Fig.14 output voltage of load cell is increased for contact force changing from 0 mg to 40 mg.

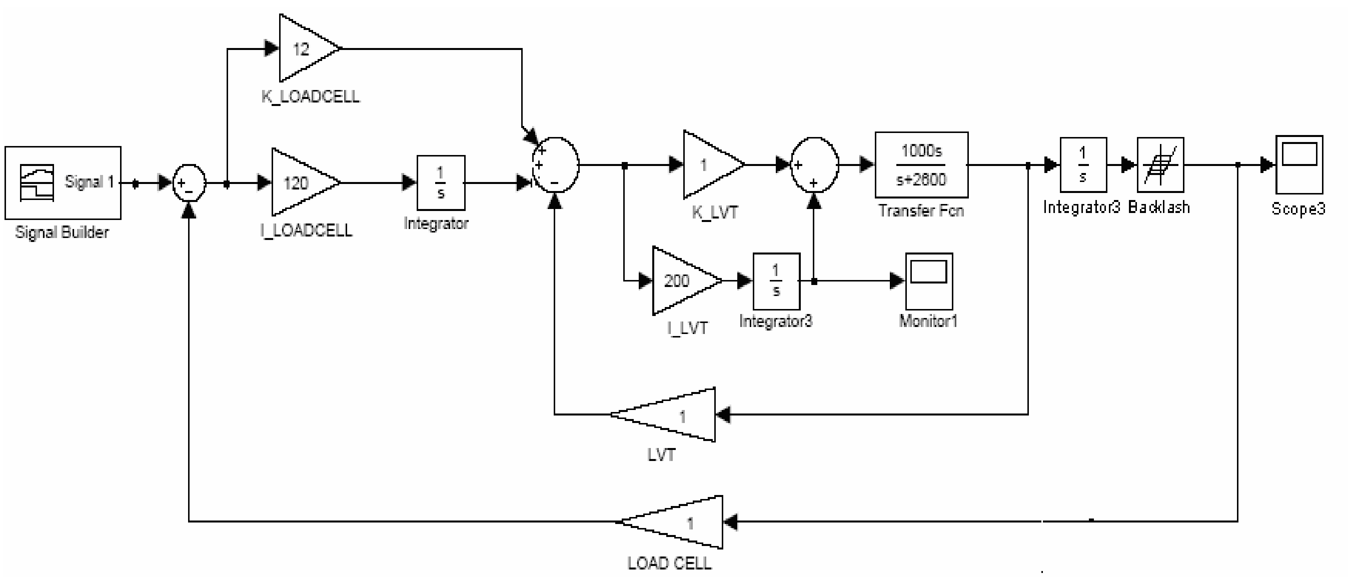


Fig.13 the design with a PI compensator and a LVT respectively in the forward and feedback paths of force actuator.

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 force 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 LVDT with the backlash parameter D to be as 0.1 and 0.3 by using a triangular input are shown in Figs. 15 and 16, respectively. 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.

III. Fuzzy Control System Design

A. Fuzzy Controller Relationship Function Design

In this section a Proportion and Derivative (PD) type fuzzy control design method is applied for the system design. It is well-known that the fuzzy controller is based on the

ISBN: 978-960-6766-77-0

ISSN 1790-5117

following IF-THEN RULE, e. g.

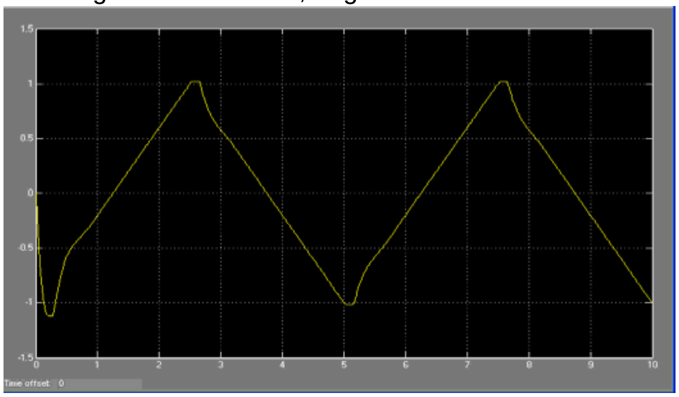


Fig. 15 output of LVDT for D=0.1 with P=1 and I=200.

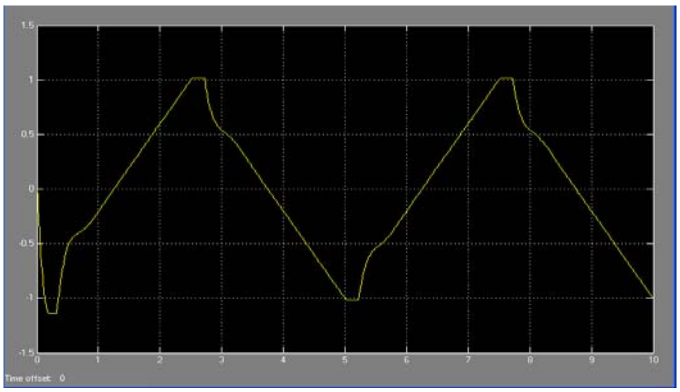


Fig. 16 output of LVDT for D=0.3 with P=1 and I=200.

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,.

The detailed cross reference rules for the inputs and output of fuzzy controller are defined in Table I. According to the fuzzy control design method the relationship functions of contact force error E, ΔE (deviations of present E and the previous E), and U (Control Input) are defined at first, which are listed in Tables II-IV. The simulation block diagram of the whole system with fuzzy controller is shown in Fig. 17.

B. *Performance Analyses with Fuzzy Controller*

Then the performance design by fuzzy controller is analyzed by simulation. Figs. 18-19 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 I
FUZZY CONTROLLER CROSS REFERENCE RULES

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

TABLE II
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 III
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 4.5 4.5]

TABLE IV
THE RELATIONSHIP FUNCTIONS OF U

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]

IV. 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. 20. For comparison purpose a commercial ET-4000 was also applied, the surface profile of which was shown in Fig. 21. Thus one can see that the performance of the proposed system was very good.

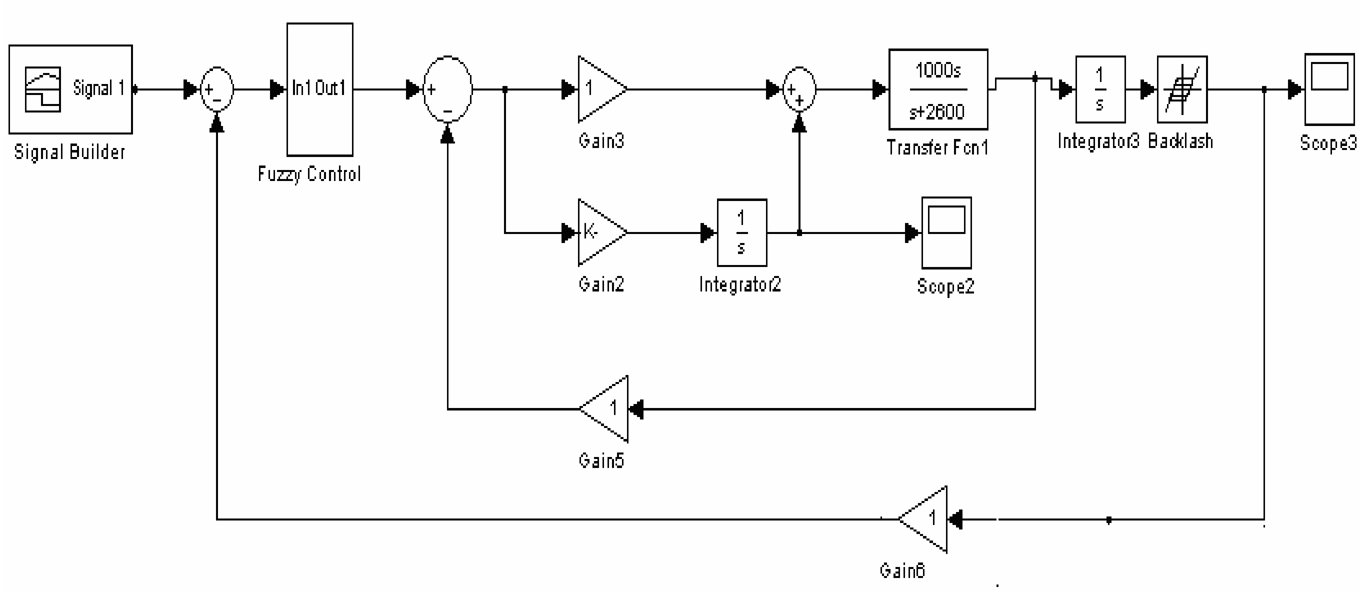


Fig.17 the design with a Fuzzy controller.

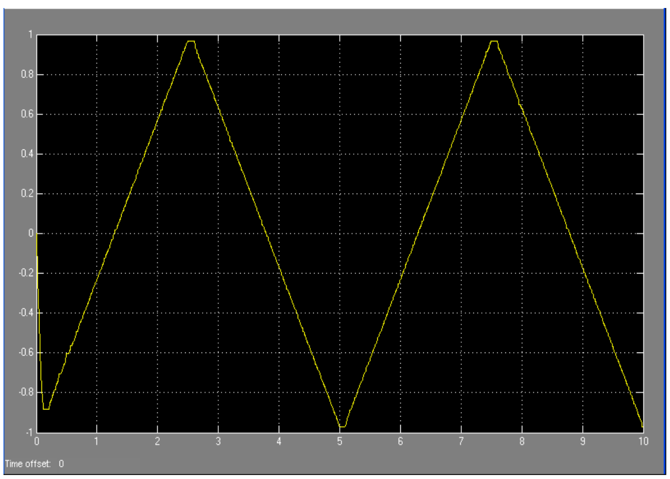


Fig. 18 output with fuzzy control for D=0.1.

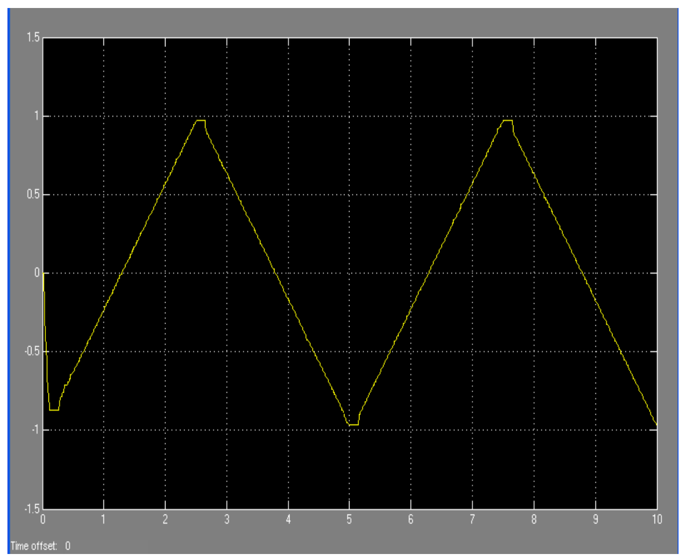


Fig. 19 output with fuzzy control for D=0.3.

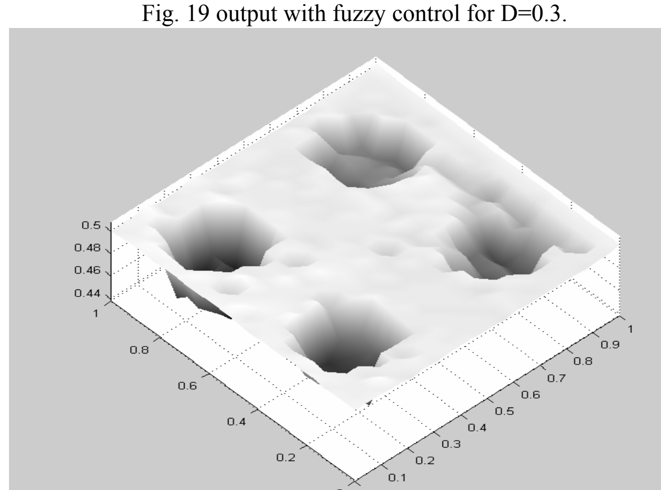


Fig. 20 the surface profile of a BGA substrate with the proposed SPM system with fuzzy controller.

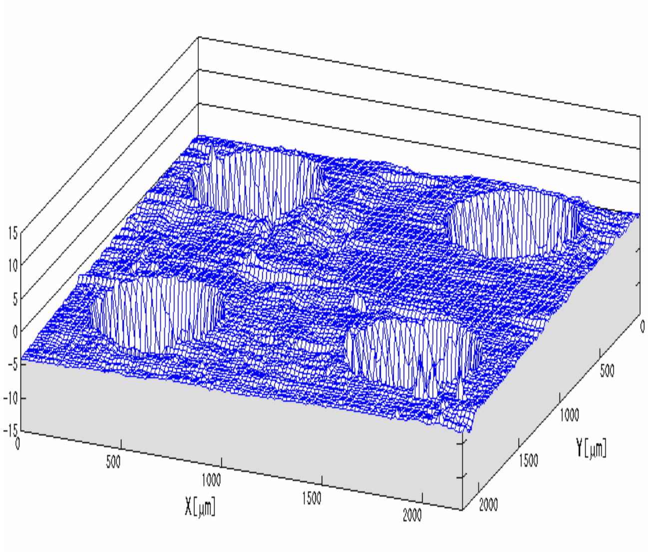


Fig.21 the profiler of a BGA substrate with ET-4000.

V. 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 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 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.

Acknowledgment

This research was supported by National Science Council under the grants of NSC 95-2221-E-216-012 and 96-2221-E-216-029-.

References

[1] D. G. Chetwyud, , X. Liu and S. T. Smith, "A Controlled-Force Stylus Displacement Probe", *Precision Engineering*, Vol. 19, No.2/3 October/ November, 1996, pp. 105–111.

[2] X. Liu, D. G. Chetwyud, S. T. Smith, and W. Wang, "Improvement of the Fidelity of Surface Measurement by Active Damping Control", *Measurement Science Techonlogy*, 1993, pp. 1330–1340.

[3] G. Neubauer, et al., "Force Microscopy with a Bidirectional Capacitor Sensor", *Rev. Science Instrument*, Vol, 61, No.9, 1990, pp. 2296-2308.

[4] M. Bennett, and J. H. Dancy, "Stylus Profiling Instrument for Measuring Statistical Properties of Smooth Optical Surfaces", *Applied Optics*, Vol. 20, No.10, 1981, pp. 1785–1802.

[5] D. G. Chetwyud, X. Liu and S. T. Smith, "Signal Fidelity and Tracking Force in Stylus Profilometry", *J. of Machinery Tools and Manufacture*, Vol. 32, No.1/2, 1992, pp. 239–245.

[6] G. Neubauer, "Force Microscopy with a Bidirectional Capacitor Sensor", *Rev. Science Instrument*, Vol. 61, 1990, pp. 2296–2308.

[7] M. Bennett, and J. H. Dancy, "Stylus Profiling Instrument for Measuring Statistical Properties of Smooth Optical Surfaces", *Applied Optics*, Vol. 20, 1981, pp. 1785–1802.

[8] J. I. Seeger, and S. B. Crary, "Stabilization of Statistically Actuated Mechanical Devices", *Electro- Transducers '97*, Chicago, IL, 1981, p. 1133.

[9] T. Gotszalk, et al., "Fabrication of Multipurpose piezo-resistive Wheatstone Bridge Cantilevers with Conductive Microtips for Electrostatic and Scanning Capacitance Microscopy", *Journal of Vacuum Science & Technology B: Microelectronics and Nanometer Structures*, Vol. 16, 1998, pp. 3948–3953.

[10] T. Gotszalk, et al., "Microfabricated Cantilever with Metallic Tip for Electrostatic and Capacitance Microscopy and Its Application to Investigation of Semiconductor Devices", *Journal of Vacuum Science & Technology B: Microelectronics and Nanometer Structures*, Vol. 22, 2004, pp. 506–509.

[11] G. Haugstad, and R. R. Jones, "Mechanisms of Dynamic Force Microscopy on Polyvinyl Alcohol: Region-Specific Non-Contact and Intermittent Contact Regimes", *Ultramicroscopy*, Vol.76, 1999, pp.77-86.

[12] V. V. Prokhorov, and S. A. Saunin, , "Probe-Surface Interaction Mapping in Amplitude Modulation Atomic Force Microscopy by Integrating Amplitude-Distance and Amplitude-Frequency Curves", *Appl. Phys. Lett.*, Vol. 91, 2007, pp. 1063–1065.

[13] J. M. Lin and C. C. Lin, "Profiler Design with Multi-Sensor Data Fusion Methods", *SICE Annual Conference 2007 in Takamatsu*, pp. 710-715, September 17-20, 2007.

行政院國家科學委員會補助國內專家學者出席國際學術會議報告

96 年 9 月 24 日

附件三

報告人姓名	林君明	服務機構及職稱	中華大學教授/研發長
會議時間地點	96 年 9 月 15 日-96 年 9 月 19 日 日本香川大學	本會核定補助文號	NSC 96-2221-E -216-029
會議名稱	（中文）國際儀表控制資訊技術 2007 年度研討會 （英文）SICE Annual Conference 2007 (International Conference on Instrumentation, Control, and Information Technology)		
發表論文題目	（中文)多重感測器整合之表面輪廓儀系統設計 （英文）Profiler Design with Multi-Sensor Data Fusion Methods		

報告內容應包括下列各項：

一、參加會議經過

這篇文章是由林君明教授，與中華大學機械與航太研究所碩士班研究生林俊杰所寫的，目的是設計一個表面輪廓儀系統。主要的方法是運用機電及光電等互不相關的多重感測器，將所獲得的機電與光電量測資訊，進行整合設計，以提升表面輪廓儀系統的精確度。由於這個方法沒有人提出過，且有經過模擬及實作驗證，所以在經過審查修改之後，終於獲得接受，並核定是口頭報告，這實在是一種榮幸。此次投稿文章總共約有 670 篇，被接受發表為 584 篇，參加投稿的有 15 個國家，由此可見此會議之規模，及受國際重視的程度。

同時國內被接受的有中正大學的羅仁權校長，台灣大學電機系的傅立成教授及連豐力助理教授，交通大學電機與控制系的徐保羅教授，中央大學電機系的鐘鴻源教授，台科大電機系的練福仁教授，聖約翰科技大學電機系的簡忠漢副教授，因此本會議由台灣來的學者專家及碩博士學生就有 10 位左右，可說是一個很大的團體。

會議每天早上九點即開始進行，揭開一天的序幕。我對表面量測及系統控制有興趣，所以就參加這方面的研討會場次，令人收穫頗多。會議期間每天都有一場演講，演講的題目分別是 ： Robotic Space Exploration Technology Development and Mission Infusion, Control and Life- From Homeostasis To Allostasis 及 The LHC at CERN: Technical Frontier Aspects of the World Largest Scientific Instrument. 這些內容是我以前比較沒有接觸過的，所以聽來是津津有味。

二、與會心得

日本不愧是亞洲的首強，從此次參加會議，不僅現場聽到作者的報告，也收集了非常多的好文章。以前只在圖書館或辦公室看論文，速度都非常慢，有些問題也沒有辦法現場就獲得解決，所以效果就打了折扣。我的研究是在表面量測及系統控制等方面，大會每天都有安

排這方面的幾篇論文發表，較不會擠在一起，所以聽起來就不會太吃力，也較不容易遺漏。有些精采的，只有會後和他們交換名片並聊一聊，這是英文程度不夠好的我們的通病。至於我自己發表文章方面，雖然在台灣已經準備的差不多了，但是到現場前兩天晚上預演時，還是覺得有些不順，而頻頻改稿子，雖然非常辛苦，但現在回想起來，收穫頗多。因為當初在投稿的時候，文章是用英文寫的，而且有篇幅的限制，所以有些觀念交代不清。現在要當場發表，怕到時後有人現場提出問題，那就麻煩了。因此前兩天都忙的很晚，講稿一改再改，睡的也很不安穩。

9月18日下午3:30，我是第一個上場，進行的非常順利，13分鐘第一次鈴響時正好講到結論，15分鐘時間到時正好結束，沒有被強制結束下台。剩下五分鐘可以給參與者發問，由於這方面我已經研究需多年了，系統各方面都比較熟悉，所以他們提出的相關問題，都可以很順利的回答，表現自評應可拿到90分。

三、考察參觀活動(無是項活動者省略)

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。

五、攜回資料名稱及內容

此次攜回的資料有光碟及會議手冊各一份。此外尚有其他研討會的預告徵稿須知如下：

1. SICE Annual Conference 2008, International Conference on Instrumentation, Control and Information, August 20-22, 2008, Univ. of Electro-Communications (UEC), Chofu, Tokyo, JAPAN.
2. INDIN 2008, 6th IEEE International Conference on Industrial Informatics, July 13-16, 2008, Daejeon, Korea.
3. IFAC 2008, The 17th World Congress on the International Federation of Automatic Control, July 6-11, 2008, COEX Convention Center, Seoul National University, Seoul, Korea.
4. DHMS 2008, 2008 IEEE International Conference on Distributed Human-Machine Systems, March 9-12, 2008, Divani Caravel Hotel, Athens, Greece.

SICE Annual Conference 2007
Sept. 17-20, 2007, Kagawa University, Japan

Profiler Design with Multi-Sensor Data Fusion Methods

Jium-Ming Lin [1] and Jiea-Chie Lin [2]

[1] Department of Mechanical Engineering, Chung-Hua University, Taiwan
(Tel : +886-3-518-6483; E-mail: jmlin@chu.edu.tw)
[2] School of Mechanical Engineering and Astronautics, Chung-Hua University, Taiwan
(Tel : +886-3-518-6484; E-mail:m09308037@chu.edu.tw)

Abstract: This research integrated a balance with stylus probe, force actuator, LVDT (Linear Variable Differential Transformer), load cell, personal computer, and XYZ-stages 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. By using PI controller, the contact-force of the probe was feedback for monitoring the force actuator to meet the desired contact-force between the probe and the object as well as to minimize the hysteresis effect of the force actuator. In order to raise the performance of the system, an optical system as well as a piezo-stage were also set up and applied, the optical system was accomplished by placing a reflective mirror at the upper middle point of balance lever arm, then a microscope as well as a CCD camera were used to detect the reflective beam displacement of a He-Ne laser. Thus one can apply the Kalman filtering technique respectively to the measurements obtained by either electro-mechanical or optical system first, and then integrating these two results by multi-sensor data fusion method to raise the performance of the system.

Keywords: Scanning Probe Microscope (SPM), contact type, surface profiler.

1. INTRODUCTION

As shown in Fig.1, this research integrated a balance with stylus probe [1-4], force actuator, LVDT (Linear Variable Differential Transformer), load cell, personal computer, and XYZ-stages 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.

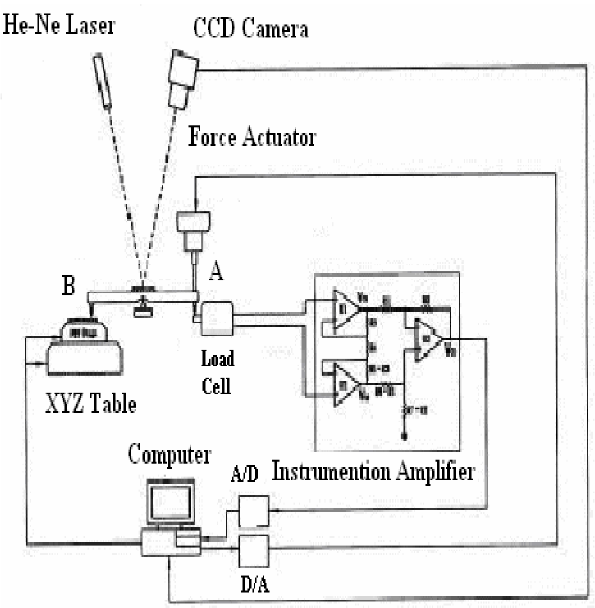


Fig. 1 The contact-force-controlled SPM system.

The stylus probe is shown in Fig.2, the voice coil was applied as a force actuator (Fig. 3a), which was equipped with LVDT (Linear Variable Differential Transformer, Fig.3b) to measure the probe vertical displacement. The load cell in Fig. 4a was used to detect the contact force between the probe and sample to be tested. A leaf spring in Fig. 4b was applied to integrate the load cell with voice coil and LVDT module as shown in Fig 4c. In addition to the XYZ-stages a piezo-stage in Fig. 5 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.

In order to raise the performance of the system, an optical system as well as a piezo-stage were also set up and applied, the optical system was accomplished by placing a reflective mirror at the upper middle point of balance lever arm, then a microscope as well as a CCD camera were used to detect the reflective beam displacement of a He-Ne laser. Thus one can apply the Kalman filtering technique [5-6] respectively to the measurements obtained by either electro-mechanical or optical system first, and then integrating these two results by multi-sensor data fusion method to raise the performance of the system.

Fig. 2 The stylus probe.

Fig. 3a Voice coil.

Fig. 3b LVDT.

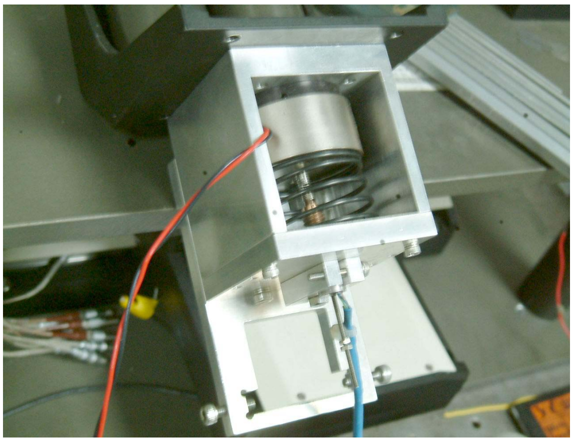


Fig. 3c Integration of voice coil and LVDT.

Fig. 4a Load cell.

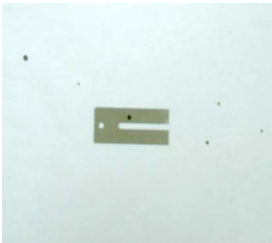


Fig. 4b Leaf spring.

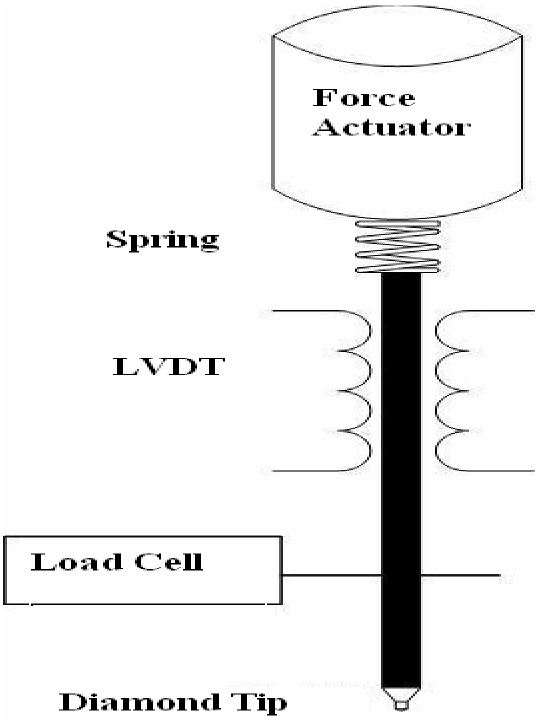


Fig. 4c Installation of load cell, voice coil and LVDT.

Fig. 5 Piezo-stage and sample holder.

Finally, the surface roughness measurements obtained by the electro-mechanical and the optical systems of a reflective mirror were made, and comparisons with that of the fusion method, it can be seen that the result of later is better.

2. PRINCIPLE OF SYSTEM OPERATION

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 shown in Fig. 6a, 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 a vertical displacement as shown in Fig. 6b. The relationship of the applied voltage and the displacement is shown in Fig. 7. In order to reduce the hysteresis-effect of the force actuator in Fig. 7, a PID compensator in the forward path as well as a LVDT measuring the vertical displacement as the feedback signal of the system, are used as shown in Fig. 8. A saw tooth shaped voltage (with peak value=100 mV) as shown in Fig. 9, which stands for the displacement command of the force actuator as well as the probe, is applied to the input of the compensated force actuator.

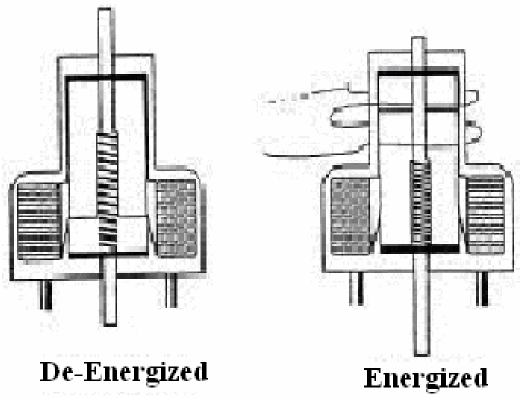


Fig. 6a De-energized, & 6b Energized of force actuator.

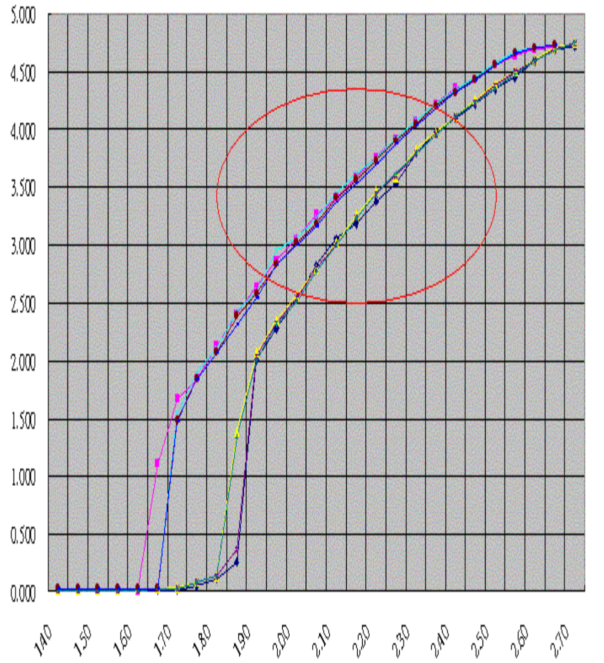


Fig. 7 The relationship of the applied voltage and the displacement of force actuator.

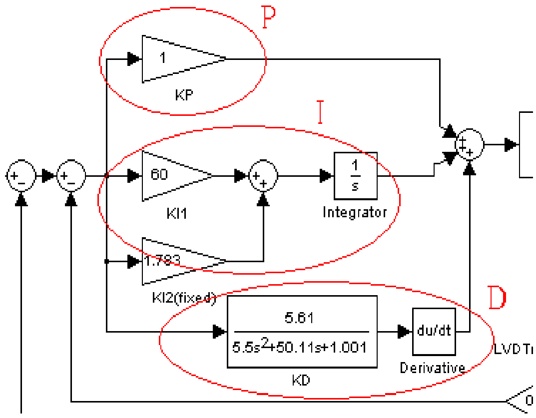


Fig. 8 The feedback system is used to reduce hysteresis effect of the actuator.

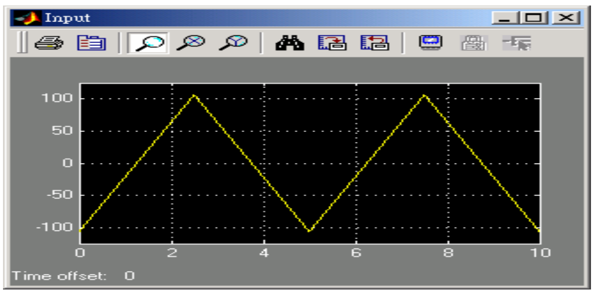


Fig. 9 A saw tooth shaped voltage (displacement command) is applied to the input of the actuator.

If the gains of the compensator are set as P=10, D=0, and I=0, respectively, then the output of LVDT is shown in Fig. 10 by MATLAB simulation. One can see the hysteresis effect still exists as shown in Fig. 11 with output and input on the x and y axes, respectively.

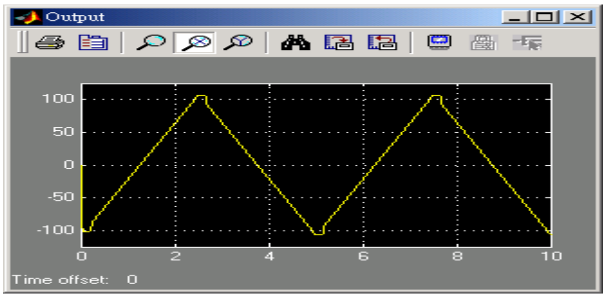


Fig. 10 The hysteresis effect still exists with P=10, D=0, and I=0.

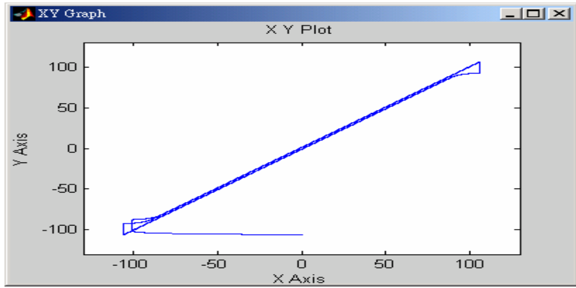


Fig. 11 The hysteresis effect still exists with P=10, D=0, and I=0.

After a little while of trial-and-error one has a very good result with P=10, D=0, and I=100, respectively, e.g. the output of LVDT is shown in Fig. 12, and the hysteresis effect is almost disappeared as shown in Fig. 13. Finally, the simulation block diagram of the whole system is shown in Fig. 14, 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.

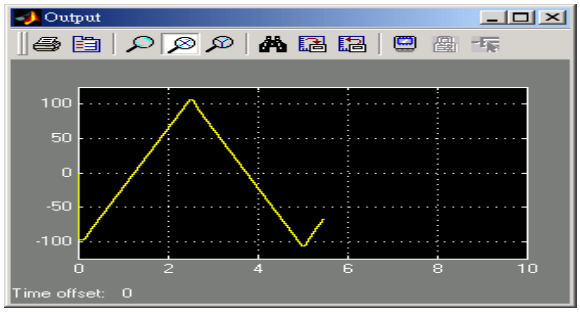


Fig. 12 The output of LVDT with P=10, D=0, and I=100.

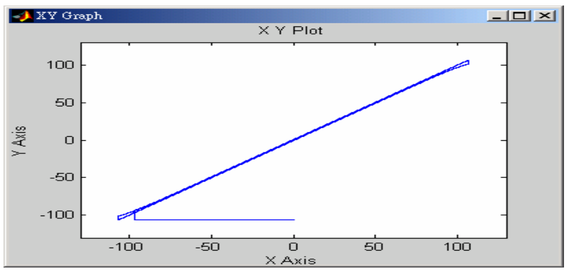


Fig. 13 The hysteresis effect is almost disappeared with P=10, D=0, and I=100.

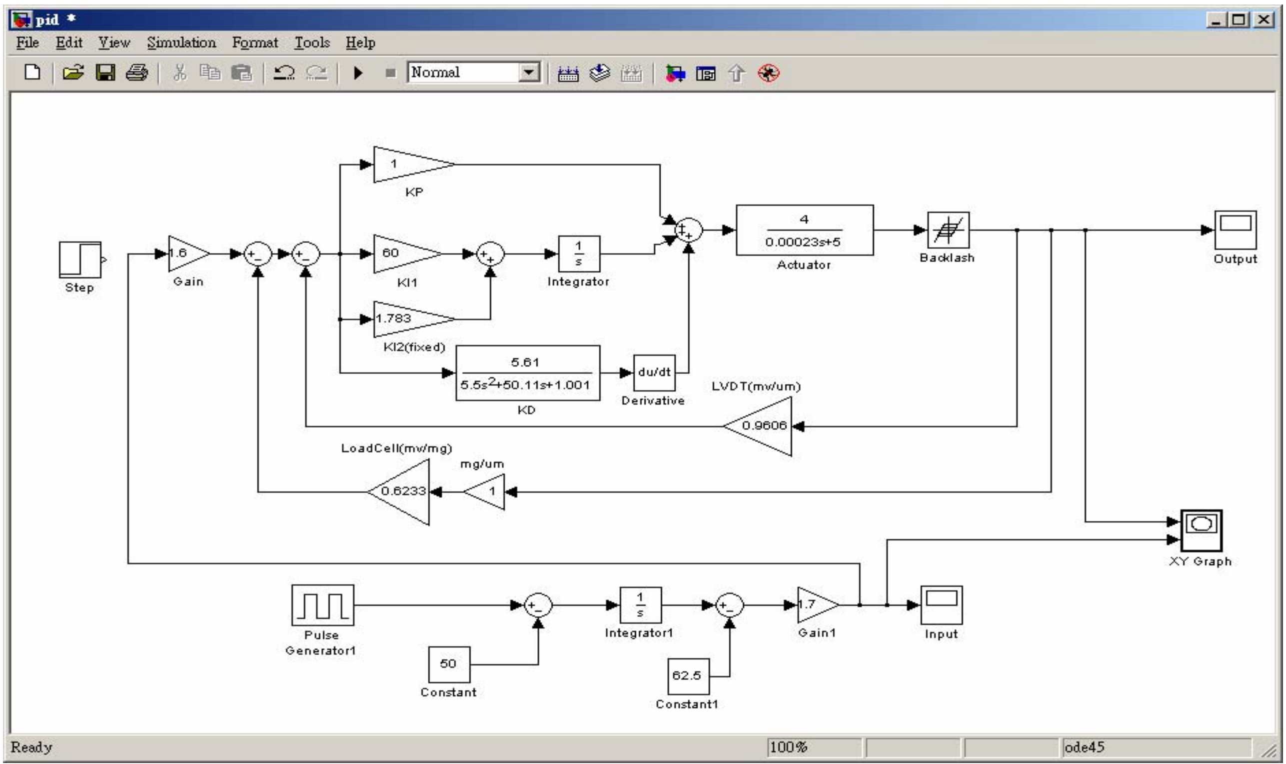


Fig. 14 Simulation block diagram of the system.

The first step of the operation is the initial leveling of the balance lever arm, which is achieved by adjusting the current through the coil of the force actuator. Since the lever arm weight at the stylus probe (contact with the sample) side is heavier than the other side (contact with the force 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-leveling height. This adjustment process stops when the value of load cell output increases from 0 mg to 40 mg as shown in Fig. 15. 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. 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. 16 from LVDT of the electro-mechanical system.

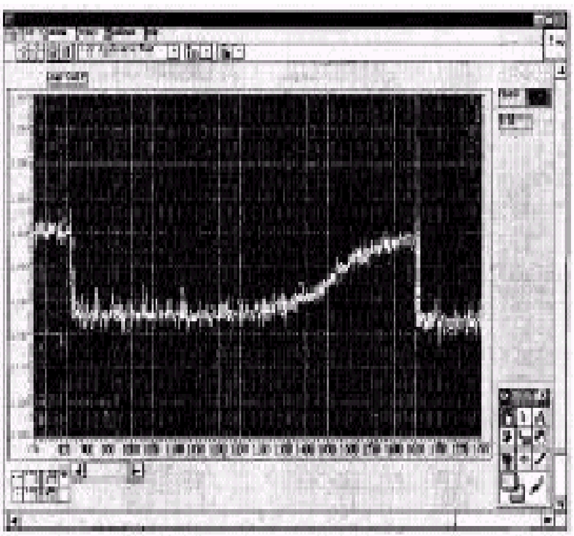


Fig. 15 The output of the load cell is increased from 0 mg to 40 mg.

Fig. 16 The profile obtained from LVDT by scanning in one dimension.

3. DATA FUSION METHOD

In order to raise the performance of the system, an optical system is also set up to make another measurement as shown in Fig.1, which is accomplished by placing a reflective mirror at the upper central point of balance lever arm, then a microscope as well as a CCD camera are used to magnify and detect the deflection displacement of a He-Ne laser beam. The operation principle of which is shown in Fig.17. If there is any vertical displacement (Δx) of the probe tip along the surface of the sample, which would cause a deflection angle (θ) of the balance lever arm (with half-length a), and the reflected angle of the laser beam would be deflected 2 θ . Then there is a displacement (h) on the CCD camera sensor. Thus from Fig.19 one has the following relationships:

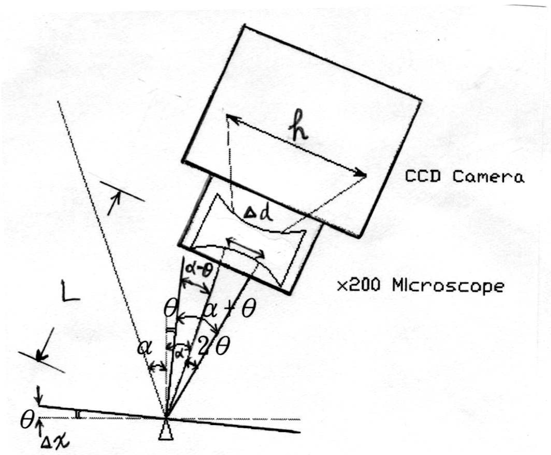


Fig. 17 The operation principle of the optical system.

.

$$\theta = \frac{\Delta x}{a} \quad , \tag{1}$$

and

$$2\theta = \frac{\Delta d}{L}, \tag{2}$$

where L is the length of microscope to the center of balance lever arm, and Δd is the displacement of reflected beam at the microscope. In addition, one has

$$\frac{h}{\Delta d} = m, \tag{3}$$

where m is the magnification factor of the microscope. By (1) to (3) one has

$$\Delta x = \frac{ha}{2mL}, \tag{4}$$

The third step is to apply the Kalman filtering technique [5-6] respectively to the measurements obtained by either electro-mechanical or optical system. The algorithm of Kalman filtering is briefed as follows:

Let the surface profile of the sample be modeled by the random bias, thus its derivative is a random walk function, i.e.

$$\dot{x} = \omega \ . \tag{5}$$

In (5) x is the surface profile of the sample, and ω is a Gaussian white noise with standard deviation σ_ω. In this research, the sample is a reflective mirror, the surface roughness of which is $\lambda/4$, where λ is the wavelength of He-Ne laser, i.e.

$$\sigma_\omega = \frac{1}{4}\lambda = \frac{1}{4}(6328)\,\mathring{A} = 1582\,\mathring{A} \ . \tag{6}$$

Thus the variance of the system noise is

$$W = \sigma_\omega^2 . \tag{7}$$

The measurement output z for the Kalman filter is taken from either electro-mechanical or optical system, i.e.

$$Z = x + v, \tag{8}$$

where v is the measurement noise. If the electro-mechanical system is applied, the accuracy of which depends on LVDT and the circuit routing condition, the standard deviation (σ_1) of which is 125 nm, and the variance V of v is

$$R = \sigma_1^2 \ . \tag{9}$$

On the other hand, if the optical system is applied, the accuracy of which depends on the pixel size of CCD camera, magnification factor of microscope and the length L in Fig. 18. Finally, the standard deviation of which is obtained as:

$$\sigma_2 = 35 \text{ nm}. \tag{10}$$

The discrete estimated state equation of the Kalman filter [6] is

$$\hat{x}_k(+) = \hat{x}_k(-) + k_k[z_k - \hat{x}_k(-)], \tag{11}$$

where $\hat{x}_k$ (+) and $\hat{x}_k$ (-) are respectively the k^{th} estimated state after and before taking the measurement z_k into consideration, and the Kalman filter gain k_k is defined as[7]

$$k_k = P_k(+)R^{-1}, \tag{12}$$

where

$$P_k(+) = E\{[\hat{x}_k(+) - \hat{x}_k]^2\}, \tag{13}$$

which is obtained by the following Algebraic Riccati Equation (ARE):

$$P_k(+) = P_k(-) - P_k(-)[P_k(-) + R]^{-1} P_k(-) \, , \tag{14}$$

or

$$P_k^{-1}(+) = P_k^{-1}(-) + R^{-1}, \tag{15}$$

where

$$P_k(-) = E\{[\hat{x}_k(-) - \hat{x}_k]^2\}. \tag{16}$$

The initial value of $P_k(-)$ is defined by equation (7), i.e.

$$P_o(-) = W \, , \tag{17}$$

and by (5) to (17), one has the filtered estimated result of electro-mechanical or optical system as

$$\hat{x}_k(-) = \hat{x}_{k-1}(+) . \quad (18)$$

The final step is to combine the filtered results of electro-mechanical and optical systems by the multi-sensor data fusion method. Since there is no correlation between these two type of measurement, and one can apply the data fusion method as follows:

$$x^* = w_1\hat{x}_{k1} + w_2\hat{x}_{k2} , \quad (19)$$

where x^* is the final integrated result, $\hat{x}_{k1}$ and $\hat{x}_{k2}$ are respectively the filtered results obtained by applying the electro-mechanical and the optical measurements, w_1 and w_2 are respectively the weighting factors of $\hat{x}_{k1}$ and $\hat{x}_{k2}$, which are defined as:

$$w_1 = \frac{\sigma_2^2}{\sigma_1^2 + \sigma_2^2} , \quad (20)$$

and

$$w_2 = \frac{\sigma_1^2}{\sigma_1^2 + \sigma_2^2} . \quad (21)$$

4. RESULTS AND CONCLUSIONS

The original and the filtered results of electro-mechanical and optical system are shown in Figs.18 and 19, respectively. The integrated one by applying the multi-sensor data fusion method is shown in Fig.20 for comparison. According to the surface roughness, usually denoted as $R_{Z\,(ISO)}$, defined by the International Standard Organization (ISO-R468) and Japanese Industry Standard (JIS-1995), i.e. by taking the average of the absolute values of the heights of five highest profile peaks and the depths of five deepest profile valleys within the sampling length, then the results of surface roughness for the measurements obtained by the electro-mechanical and the optical systems are 1660 Å and 1534Å , respectively, which are reasonable according to the specification (1582 Å) of the reflective mirror. In addition, if one uses the data fusion method, then the resulting surface roughness is 1526 Å, which is better than that by using either electro-mechanical or optical system.

ACKNOWLEDGMENT

This research was supported by National Science Council Taiwan, R. O. C. with the grant no: NSC-95-2221-E-216-012-.

REFERENCES

[1] D. G. Chetwyud, X.Liu and S.T. Smith, "A Controlled-force Stylus Displacement Probe," Precision Engineering, Vol. 19, No.2/3 Oct./Nov., pp.105-111, 1996.

[2] M. Bennett and J.H. Dancy, "Stylus Profiling Instrument for Measuring Statistical Properties of Smooth Optical Surfaces," *Applied Optics*, Vol. 20, pp. 1785-1802,1981.

[3] X. Liu, D.G. Chetwyud and S.T. Smith, " Improvement of the fidelity of surface measurement by active damping control," *Meas. Sci. Technol,* Vol. 4, pp. 1330-1340, 1993.

[4] J. I. Seeger and S.B. Crary, "Stabilization of Electro-Statistically Actuated Mechanical Devices," Transducers '97, Chicago, IL, p. 1133, 1997.

[5] P. S. Maybeck, *Stochastic Models, Estimation and Control*, Vol. 1, Academic Press, 1990.

[6] R. G. Brown, *Introduction to Random Signal Analysis and Kalman Filtering*, Wiley, New York, 1983.

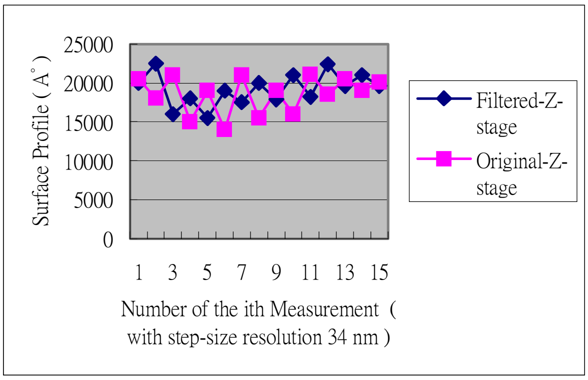


Fig. 18 The original and the filtered results of electro-mechanical system.

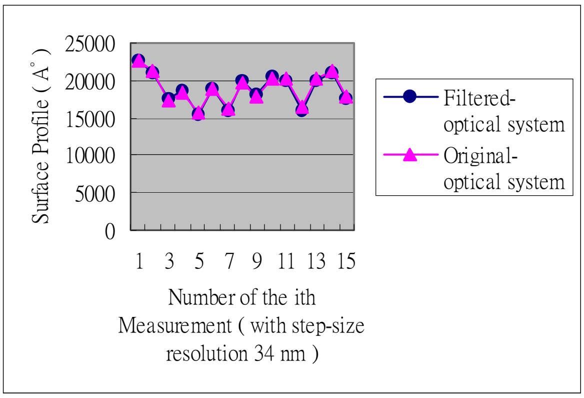


Fig. 19 The original and the filtered results of optical system.

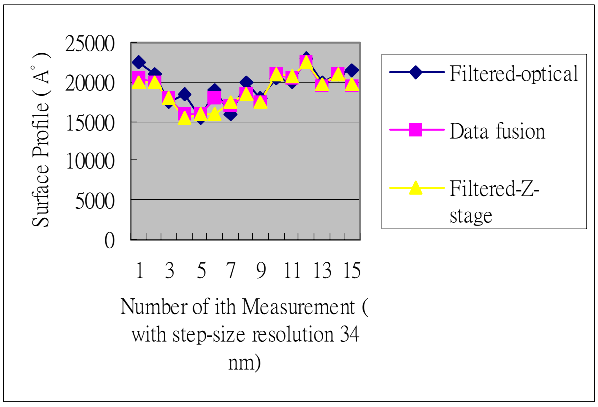


Fig. 20 Comparisons with the results of filtered electro-mechanical, optical systems and data fusion methods.

行政院國家科學委員會補助國內專家學者出席國際學術會議報告

96 年 9 月 24 日

附件三

報告人姓名	林君明	服務機構 及職稱	中華大學教授/研發長
會議 時間 地點	96 年 9 月 15 日-96 年 9 月 19 日 日本香川大學	本會核定 補助文號	NSC 96-2221-E -216-029
會議 名稱	（中文）國際儀表控制資訊技術 2007 年度研討會 （英文）SICE Annual Conference 2007 (International Conference on Instrumentation, Control, and Information Technology)		
發表 論文 題目	（中文)多重感測器整合之表面輪廓儀系統設計 （英文）Profiler Design with Multi-Sensor Data Fusion Methods		

報告內容應包括下列各項：

一、參加會議經過

這篇文章是由林君明教授，與中華大學機械與航太研究所碩士班研究生林俊杰所寫的，目的是設計一個表面輪廓儀系統。主要的方法是運用機電及光電等互不相關的多重感測器，將所獲得的機電與光電量測資訊，進行整合設計，以提升表面輪廓儀系統的精確度。由於這個方法沒有人提出過，且有經過模擬及實作驗證，所以在經過審查修改之後，終於獲得接受，並核定是口頭報告，這實在是一種榮幸。此次投稿文章總共約有 670 篇，被接受發表為 584 篇，參加投稿的有 15 個國家，由此可見此會議之規模，及受國際重視的程度。

同時國內被接受的有中正大學的羅仁權校長，台灣大學電機系的傅立成教授及連豐力助理教授，交通大學電機與控制系的徐保羅教授，中央大學電機系的鐘鴻源教授，台科大電機系的練福仁教授，聖約翰科技大學電機系的簡忠漢副教授，因此本會議由台灣來的學者專家及碩博士學生就有 10 位左右，可說是一個很大的團體。

會議每天早上九點即開始進行，揭開一天的序幕。我對表面量測及系統控制有興趣，所以就參加這方面的研討會場次，令人收穫頗多。會議期間每天都有一場演講，演講的題目分別是 ： Robotic Space Exploration Technology Development and Mission Infusion, Control and Life- From Homeostasis To Allostasis 及 The LHC at CERN: Technical Frontier Aspects of the World Largest Scientific Instrument. 這些內容是我以前比較沒有接觸過的，所以聽來是津津有味。

二、與會心得

日本不愧是亞洲的首強，從此次參加會議，不僅現場聽到作者的報告，也收集了非常多的好文章。以前只在圖書館或辦公室看論文，速度都非常慢，有些問題也沒有辦法現場就獲得解決，所以效果就打了折扣。我的研究是在表面量測及系統控制等方面，大會每天都有安

排這方面的幾篇論文發表，較不會擠在一起，所以聽起來就不會太吃力，也較不容易遺漏。有些精采的，只有會後和他們交換名片並聊一聊，這是英文程度不夠好的我們的通病。至於我自己發表文章方面，雖然在台灣已經準備的差不多了，但是到現場前兩天晚上預演時，還是覺得有些不順，而頻頻改稿子，雖然非常辛苦，但現在回想起來，收穫頗多。因為當初在投稿的時候，文章是用英文寫的，而且有篇幅的限制，所以有些觀念交代不清。現在要當場發表，怕到時後有人現場提出問題，那就麻煩了。因此前兩天都忙的很晚，講稿一改再改，睡的也很不安穩。

9 月 18 日下午 3:30，我是第一個上場，進行的非常順利，13 分鐘第一次鈴響時正好講到結論，15 分鐘時間到時正好結束，沒有被強制結束下台。剩下五分鐘可以給參與者發問，由於這方面我已經研究需多年了，系統各方面都比較熟悉，所以他們提出的相關問題，都可以很順利的回答，表現自評應可拿到 90 分。

三、考察參觀活動(無是項活動者省略)

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。

五、攜回資料名稱及內容

此次攜回的資料有光碟及會議手冊各一份。此外尚有其他研討會的預告徵稿須知如下：

1. SICE Annual Conference 2008, International Conference on Instrumentation, Control and Information, August 20-22, 2008, Univ. of Electro-Communications (UEC), Chofu, Tokyo, JAPAN.
2. INDIN 2008, 6th IEEE International Conference on Industrial Informatics, July 13-16, 2008, Daejeon, Korea.
3. IFAC 2008, The 17th World Congress on the International Federation of Automatic Control, July 6-11, 2008, COEX Convention Center, Seoul National University, Seoul, Korea.
4. DHMS 2008, 2008 IEEE International Conference on Distributed Human-Machine Systems, March 9-12, 2008, Divani Caravel Hotel, Athens, Greece.