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Making a High-Precision Positioning Apparatus by an Optical Pickup Head Module

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***Abstract*—A linear moving stage using a commercially available optical pickup head as the key element of the whole system was constructed. An additional object carrier was rigidly mounted to the lens module so that the carrier moved synchronically and consistently with the lens module. The carrier platform can carry light weight objects, such as bio-cells for manipulation or optical fiber in alignment application. A CD holder with a small part of optical disk taken from a CD was located in front of the lens module. The focusing error signal from the photo diode was used to indicate the position between the carrier platform and the CD. A digital lead compensator with integrator was implemented to improve the transient response and positioning accuracy. Experimental results showed that the moving stage with the above arrangement can successfully achieve the positioning for micro, submicron and 50nm position commands within the overall moving range of 10 μm. The feasibility of creating a low cost accurate positioning system using an optical pickup head module was successfully demonstrated in the architecture. The cost of the precision positioning system is far cheaper than other precision positioning systems nowadays. The concept of the proposed positioning apparatus can be further extended into making a two stage of moving in X and Y directions by together using focusing and radial error signals at the same time.**

I. INTRODUCTION

In recent years, high precise positioning systems have gradually become one of the necessary equipments in producing high value-added products in, such as semiconductor sector, fiber optics and bio-inspection area etc. For example, in 2003, 193nm lithography was brought in mass manufacturing, and patterning was able to scale down to the 65nm node in mask technology [1]. Precision Positioning is still going very rapidly down to even smaller scale with the same pace as nanotechnology. Among these high-precision positioning systems [2][3][4], two main categories of actuators, namely the piezo-electric and electric-magnetic actuators, play important roles in implementing the nano-scale motion with high response speed for the moving stages.
However, those positioning systems are accompanied by various high cost elements, such as piezo-actuator, capacitor position sensor, laser interference meter, or magnetic levitators etc, and make the whole system very expensive for the users. In this paper, we target at proposing a cheap solution for achieving high-precision positioning by using one of the common components in consumer electronics in optical storage devices. Optical storage devices such as CD-ROM/ DVD-ROM drives have gradually dominated the storage market and become one of the most popular devices for multi-media backup. One CD-ROM is capable of containing digital data up to 750MB, and a DVD-ROM even to 4.7GB for a standard disk size of 12mm in diameter[5][6]. In order to fulfill the large quantity of memory, the physical arrangement of pits on the CD/DVD has to be in very high density. These pits are arranged in spiral tracks with the track pitch 1.6 μm for CD and 0.74 μm for DVD. Laser spots have to be correctly sent onto the right track and in focal location so that the intensity of the reflected laser beams are sensed and demodulated and digital data were restored. As a result, the device for retrieving data is required to have the ability of achieving high positioning accuracy and rapid response characteristics for high speed data reading. Currently, the voice coil motor (VCM) of an optical pickup head (OPU) is designed to be able to move the optical lens module within the sub-micro accuracy and achieves bandwidth of more than 50Hz to meet the data reading specifications of CD-ROM/ DVD-ROM. All the other components, such as mechanical suspension system, optics-electro system and electronic system on the OPU are also manufactured to meet the requirement. Although the pickup head has high performance of positioning, the cost of a pickup head is very cheap due to strong competition of the optical storage market. Nowadays, one OPU for 52x CD-ROM drive has been reduced to less than USD$ 10 dollars and still possible to drop. Combing the two advantages of cheap price and high performance in positioning, we made a very competitive positioning system. The optical pickup head taken from a CD-ROM/DVD-ROM drive was used the moving stages which provided two voice coil motors for linear motion in two orthogonal directions, and laser feedback signals for position measurement.

II. SYSTEM DESCRIPTION

A commercially available optical pickup head (OPU) as shown in Fig. 1, costs less than USD$10 dollars, but consists of very high accurate optical-mechanical-electro components in order to read signals from very dense tracks in multi-media discs, such as CD or DVD. The lens modules of an OPU is suspended by 4 strings with dampers and moved in lateral and longitudinal directions by two voice coil motors. One object carrier platform made by aluminum was mounted

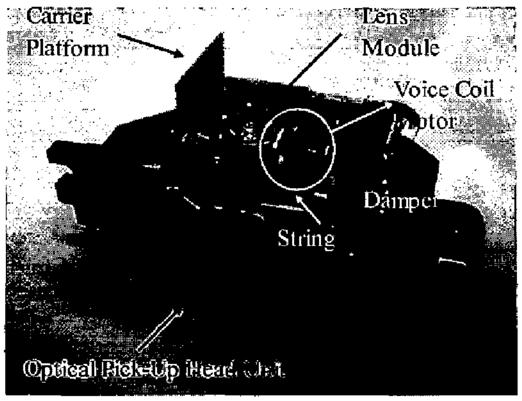


Fig.1 A Commercially Available Optical Pickup Head Module with Carrier Platform Mounted to its Lens Module

onto the lens module. It is reasonably assumed that the carrier platform and the lens module are rigid to each other and they move at the same pace. Therefore, the position of the carrier platform can be obtained by measuring the position of the lens module. Firstly, we started our study at looking at the focusing direction of the positioning system. The positioning system in focusing direction was consisted of three subsystems: mechanical part, signal processing part and digital controller.

A. Mechanical Stand Unit

The mechanical part holds a trimmed CD piece located at the front of the OPU, as shown in Fig. 2.

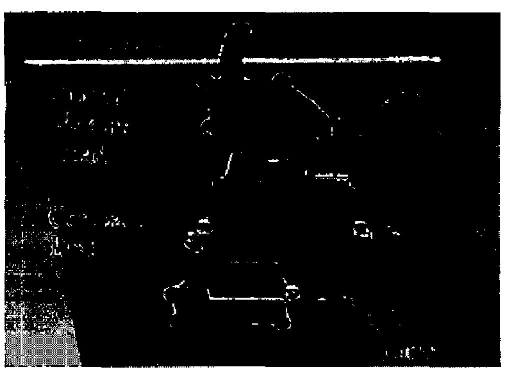


Fig.2 An Optical Pickup Head Module with Carrier Platform is Embedded to a Mechanical Frame with a Small Piece of CD at the Front

The CD piece is rigidly fixed to the whole base and the carrier platform moves relative to it can be obtained by reading the reflected optical signal from the pickup head. The astigmatic method, (i.e. the focal points with respect to the vertical and horizontal axes will change according to the light source position), generates the focusing error with an "S-curve" shape of signals in the total range of movement. The focusing error voltage, i.e., the voltage related to focusing error, is positive when the lens module moves toward

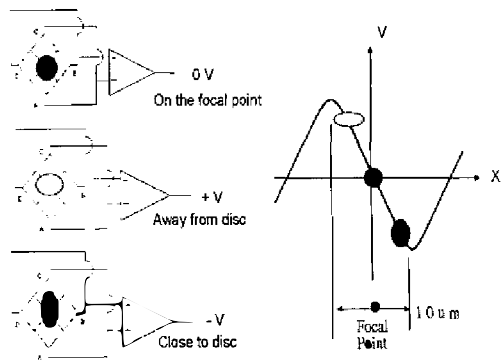
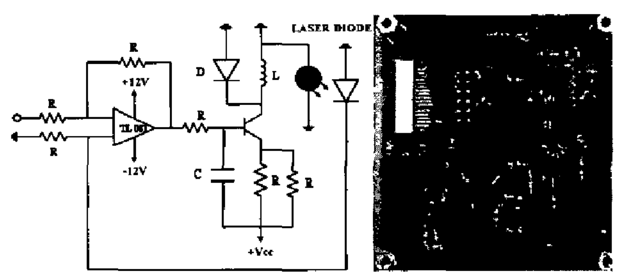


Fig.3 S-curve of the Focusing Error Voltage versus Displacement in the Focusing Direction

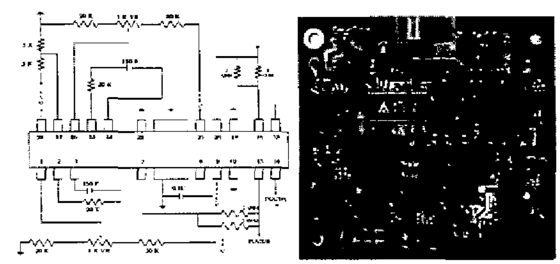
the disc; negative when away from the disc. At the linear region of the S-curve, a linear relationship between the distance of lens and disc and the focusing error exists [7]. Therefore, the focusing error voltage is very suitable to be used as a position sensor with very high precision [8]. Compared with other kinds of position sensor, such as laser interferometer or capacitance position sensor, this type of position sensor has advantage of very cheap price with similar level of measuring scale.

B. Electronic Circuit Unit for Signal Processing

The second part of the system is the signal processing unit, which includes laser driving circuit, focusing error amplification circuit and motor driving amplifier.



(a)



(b)

Fig.4 Signal Processing Board for (a) Output Power of Laser, (b) Output Current of Voice Coil Motor

The main purpose of the laser power density control circuit is to maintain a constant power output of laser diode through a feedback photo diode signal. The laser spot from the laser diode is emitted and reflected to the 4-quarant photo detector mounted on lens module is then transformed into electric signals. Another signal processing circuitry is to calculate the focusing error

$$V_f = L_g(V_A + V_C - (V_B + V_D))$$

where: V_A, V_B, V_C, V_D is the voltage output of each photo diode channel
V_f is the focusing error
L_g is the amplification gain

The amplification gain L_g is adjusted so that the linear region of focusing error matches the range of $\pm 5V$ so the maximal resolution between the position and focusing error can be achieved.
On the other hand, the control output send from controller needs to be attenuated before being sent to the motor driver IC. The driver IC we used in this paper could output a significantly large signal to the voice coil motor so that one bit of signal sent from DAC channel is still too large to control the carrier platform move for fine motion. Therefore, 1000 times voltage level attenuation is used and tiny motion become possible.

C. Digital Controller Implementation

When a reference position command is given, the digital controller computes a corresponding control signal output and the motor driver outputs control signal to the voice coil motor. The voice coil motor moves the lens module and the object carrier platform moves synchronously. The actual position is measured by the 4-quadrant photo detector using astigmatic method Focusing error is obtained after appropriate processing the output of the photo detector. At this stage, a digital phase lead compensator plus a digital integrator was implemented to improve the transient response and steady state behavior of the positioning system. The sampling rate was chosen 10KHz since the operation bandwidth for the positioner was set under 100Hz. 100 times faster than the system operation bandwidth is adequate to fulfill the performance requirement.

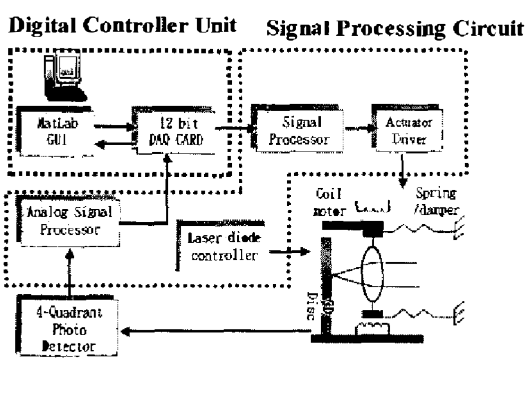


Fig.5 Block Diagram of the Overall Positioning System

The digital controller is implemented by using xPC structure based on Matlab™ toolbox. An NI-6024E DAQ card was selected and accompanied to the Pentium-4 PC as shown in Fig. 6.

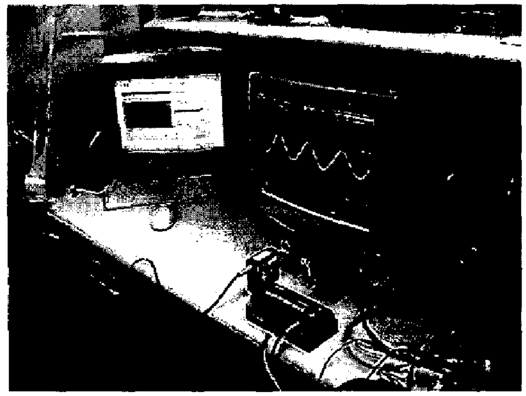


Fig.6. Digital Controller Was Implemented by an xPC Structure with Simulink™

III. Experimental Results and Discussions

The experimental setup integrates the mechanical part, signal processing circuit board and xPC digital controller as shown in fig. 7. The position of the carrier platform is referred to the focal point of the lens module with respect to CD plate. A laser interferometer was also setup to measure the displacement of the carrier platform for the purpose of verification. A pre-determined position trajectory is given to the master PC and position tracking is fulfilled by the target PC. The measured signals by the target PC can be shown on the monitor and saved in the master PC.

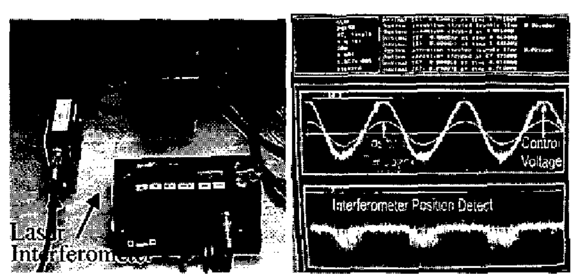


Fig.7 Experimental Setup of the Overall Positioning System with Verification of an Laser Interferometer

Three different ranges of positioning capabilities were tested. Step response of the open loop was also investigated under no load and with 10 gram payload. Subsequently step response of close loop at three different range of position command: 2 μm, 0.2 μm and 50 nm were tested under no load and payload situations.

A. Open Loop Positioning

A reference positioning step command from 0 μm to 2 μm is given, which is correspondent to a reference voltage from 0V to 2V. Experimentally, we adjusted the amplified gain of control output voltage so that ±5V of control output voltage can approximately drive the carrier platform to move in ± X-axis with position feedback signal of ±5V. In other word, 2V of control output voltage can approximately move the carrier platform 2 μm in + X axis. Fig. 8(a) shows that the starting point of the carrier platform stayed at 0.5 μm and final position of the carrier platform reached 1.8 μm. In addition, Fig. 8(b) shows that the starting point of the carrier platform stayed at 1.5 μm and reached around 3.3 μm under 10 grams payload.

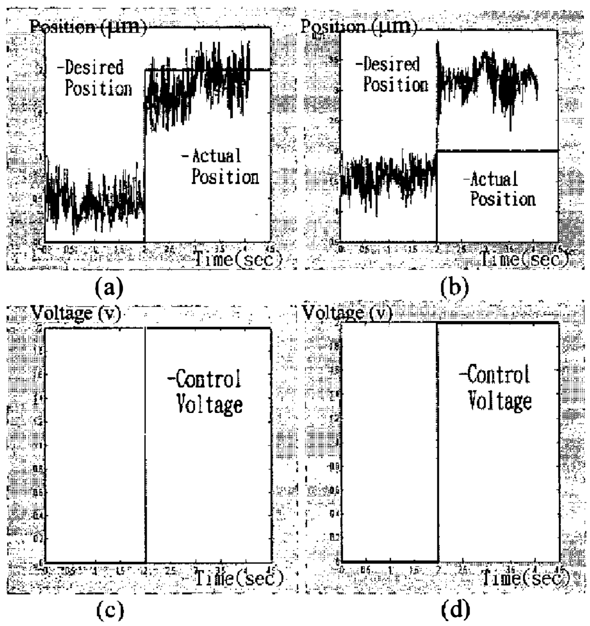


Fig.8 Step Response of the Open Loop System, (a)& (b) Position and Control Signal without Payload, (c)&(d) Position and Control Signal with Payload

The data showed that 2V control voltage could approximately drive the voice coil motor to generate a force to counter the spring force of strings on the lens module by around 1.8 μm away from its equilibrium point. This is also why the starting point varied so significantly when payload was added. In other words, open loop architecture for positioning is not suitable for the system.

B. micro scale positioning

On the other hand, a close loop positioning system for 2 μm step command was tested. Observation from Fig. 9(a) and (b), the starting and ending point of the carrier platform could follow the desired position command. The ripple on the focusing error is also smaller than Fig 8(a) and (b) of open loop case. The controller could effectively provide damping to the system and suppress the vibration of carrier platform. Steady state error was also greatly improved.

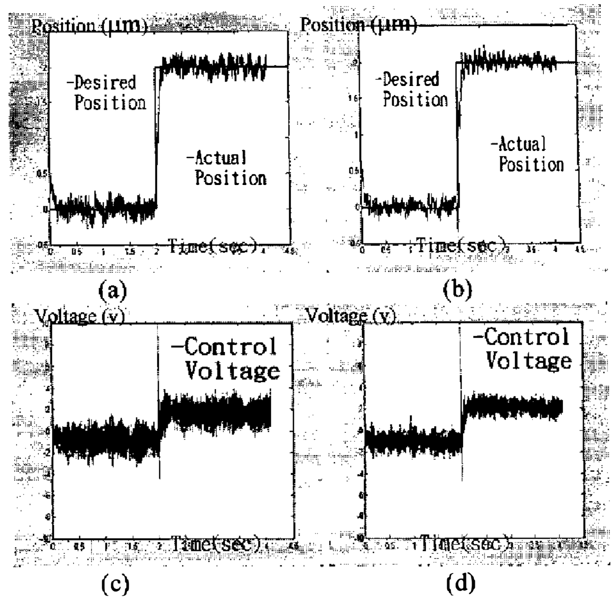
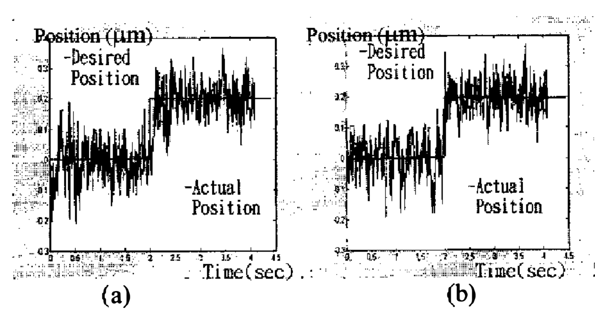


Fig.9. Response of the Closed Loop System for 2 μm Step Command, (a)& (b) Position and Control Signal without Payload, (c)&(d) Position and Control Signal with Payload

The control voltage for the 0 μm position is about -1.0V in the no load case and -1.2V in the payload case. This indicates that a correction force to the position deviation of the carrier platform from the equilibrium was needed. The closed loop system was able to maintain the same starting point. The payload caused a larger deviation of carrier platform from the origin point so that -1.2V was exerted with payload than -1.0V without payload. Similarly, the control voltage for final position under payload was 2.2V, which is also higher than 2.0V under no payload. The increased damping ratio due to payload was also observed from comparing the ripples on the position and control signals. The ripple of about 0.5 V rms of no payload case was smaller than about 0.8V rms of payload case. The payload effect on the position apparatus was not serious in terms of rising time and steady state error in the closed loop system.

C. Sub-micro scale positioning

Sub-micro positioning capability was investigated by setting a step command of 0.2 μm.



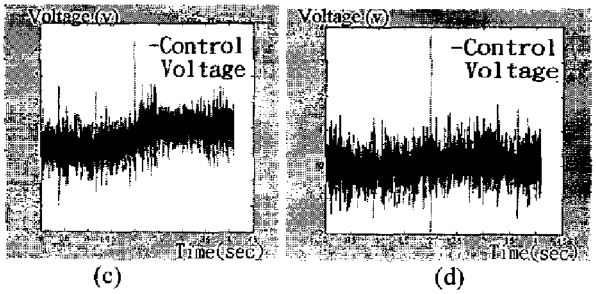


Fig. 10 Response of the Closed Loop System for 0.2 μm Step Command, (a)& (b) Position and Control Signal without Payload, (c)&(d) Position and Control Signal with Payload

Observation from Fig. 10 indicates that the closed loop system achieved the desired position tracking with rising time around 0.1 msec. Payload effect was apparently minor.

D. nano scale positioning

In the test, a 50mm position step command was given. Fig. 11 shows the experimental results. Both cases of with and without payload could demonstrate the ability of 50nm position resolution. The ripples on the position signal are significantly large. However, the movement of carrier platform was verified by looking at the mean value of the position signal. The average value showed the 50nm moving was possible.

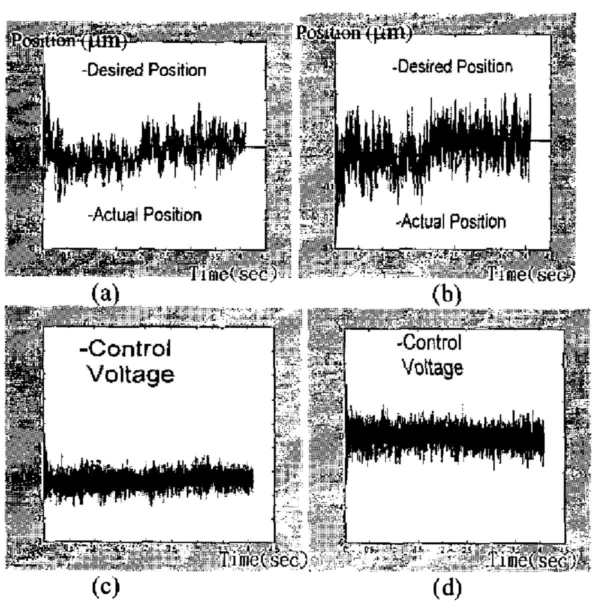


Fig. 11. Response of the Closed Loop System for 50nm Step Command, (a)& (b) Position and Control Signal without Payload, (c)&(d) Position and Control Signal with Payload

Obviously, the problem in verifying nano-positioning capabilities is due to the environment noise, such as mechanical vibrations or electro-magnetic interference, which could easily contaminate the measured position signal. No sooner the sources are identified, which giving rise to the ripple observed from the position signal, than a signal low pass filter can be applied. If the ripples are partly caused by the vibration of the carrier platform no matter because of motor coil actuation or environment vibration, any low filtering of the signal is certainly not suitable. The consequence would prevent the system from measuring the mechanical vibration and make the controller unable to suppress the vibration of the system position output. On the other hand, if the ripple was due to electro-magnetic noise and the noises could be decoupled from the mechanical vibration mode, then a suitable filter can be applied and suppress the level of the ripple. More clarifications for the source of ripples will be investigated in the future.

IV. Conclusion and Future Work

In this paper, we constructed a linear moving stage using a commercially available optical pickup head as the main body of the whole system. An OPU is a typical optics-electro and mechatronics integrated system. It contains optics-electro components, such as laser diode, photo diode and lens modules to generate laser beam, to detect reflected laser beam and to direct the laser beam. It also contains mechatronics components, such as voice coil motors to move the lens module in focusing and radial directions, spring and damper system attached to the lens module to hold and constrain its motion behavior. We made an object carrier which was rigidly mounted to the lens module so that the carrier moved synchronically and consistently with the lens module. The carrier platform can carry light weight objects, such as bio-cells for manipulation or optical fiber in alignment application. In addition, a CD holder with a small part of optical disk taken from a CD was located in front of the lens module. The distance between the lens module and optical disk is obtained from the measuring the laser beam intensity reflected from the optical disk. Using astigmatism method, the intensity of the reflected laser beam distributed on four photo cells will be changed according to the lens locations. Through the appropriate signal processing, an "S-curve" can be found when moving the lens module from the furthest to the nearest. Because the linear region of the "S-curve" arisen from the movement of the platform in the focusing direction has the linear relationship between the output voltage of focusing error and the displacement of laser spot from focal point, the focusing error signal can be used to indicate the position of the platform after suitable signal processing. A signal processing circuit board with suitable amplification and low pass filter was designed. The processed focusing error signals were sent to a personal computer through an NI PCI 6024E AD/DA interface card.

The position controller was implemented by a lead-lag compensator with sampling rate of 10 kHz. The control inputs were calculated and sent from the AD/DA card to the VCM with suitable analog attenuation so that the control resolution could be augmented. Careful dealing with the upper and lower bound of control output is important because too large control output can cause the lens modules go out of the linear region of the S-curve and system will go unstable. The determination of upper and lower bound was done through the auto-calibration process. Experimental results showed that the moving stage with the above arrangement can successfully demonstrate the overall system was able to achieve the positioning for submicron and 50nm position commands.

The proposed high-precision positioning apparatus was able to achieve nano scale movement in 50nm resolution with total range of 10 μm. The paper proposes a positioner, which can offer a simpler structure with cheaper price than other kinds of high-precision positioner driven by piezo-actuators. With its low cost and high precision, we believe the positioner can be applied in many fields. In the future, we will extend the stage into 2 stages by including the radial motion of voice coil motor of the optical pickup head to enable the carrier platform to follow a plane trajectory.

V. REFERENCES

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