Design of a dual-axis optoelectronic level for precision angle measurements

2011 Meas. Sci. Technol. 22 055302

(http://iopscience.iop.org/0957-0233/22/5/055302)

IOP PUBLISHING MEASUREMENT SCIENCE AND TECHNOLOGY
Meas. Sci. Technol. **22** (2011) 055302 (7pp) doi:10.1088/0957-0233/22/5/055302

Design of a dual-axis optoelectronic level for precision angle measurements

Kuang-Chao Fan[1,3], Tsung-Han Wang[1], Sheng-Yi Lin[1] and Yen-Chih Liu[2]

[1] Department of Mechanical Engineering, National Taiwan University, Taipei, Taiwan
[2] Metal Industries Research & Development Centre, Kaohsiung, Taiwan

E-mail: fan@ntu.edu.tw

Received 3 January 2011, in final form 13 March 2011
Published 13 April 2011
Online at stacks.iop.org/MST/22/055302

Abstract
The accuracy of machine tools is mainly determined by angular errors during linear motion according to the well-known Abbe principle. Precision angle measurement is important to precision machines. This paper presents the theory and experiments of a new dual-axis optoelectronic level with low cost and high precision. The system adopts a commercial DVD pickup head as the angle sensor in association with the double-layer pendulum mechanism for two-axis swings, respectively. In data processing with a microprocessor, the measured angles of both axes can be displayed on an LCD or exported to an external PC. Calibrated by a triple-beam laser angular interferometer, the error of the dual-axis optoelectronic level is better than ±0.7 arcsec in the measuring range of ±30 arcsec, and the settling time is within 0.5 s. Experiments show the applicability to the inspection of precision machines.

Keywords: optoelectronic level, dual-axis, DVD pickup head, pendulum mechanism, angle measurements

(Some figures in this article are in colour only in the electronic version)

1. Introduction

Precision engineering level is a very fundamental metrological tool for absolute angle measurement of out of earth level. It is frequently applied to the machine bed leveling of the ground during installation [1], flatness error measurement of a precision surface plate [2], comparative height measurement [3], or angular error measurement of a linear slide or moving stage [4]. Although there have been many kinds of precision angle measurements, for instance, with a laser interferometer [5], MEMS accelerometer [6], fiber-optic sensor [7], or moiré-fringe effect [8], they are not actually for out-of-level measurement. As an industrial level, its structure must have a reference to gravity, typically with a pendulum mechanism or a moving bubble. For the pendulum type, its swing is detected by non-contact sensors. Conventional commercial precision levels are all of this type, e.g. capacitive sensor used in the Leveltronic of Wyler Co. [9] and the inductive sensor used in the Talyvel of Taylor Hobson Co. [10]. However, all these precision levels are only in one axis. Repeated change from one axis to the other is inevitable when applying the one-axis level for installing a machine to the ground. It is more suitable if a dual-axis level can be used. A bubble level, although it can provide dual-axis readings, cannot read precisely its bubble displacement on the vial scale. Modern technology employing light source and photo sensors to detect bubble position can output digital signals and link to the computer for data analysis, such as the electronic level wafer of Brooks Automation Co. [11] and the multi-axis bubble vial device [12], but the resolution and accuracy are not as good as the pendulum type. For the purpose of measuring angular errors of precision machines, this study, therefore, aims at the design of a pendulum-type dual-axis precision level. A similar design concept of the pendulum mechanism for dual-axis angular motion measurement has been applied to the dual-axis accelerometer [13] and optoelectronic level [14]. Unfortunately, neither considered the damper design, which is very important to the precision level as the swing has to be stopped as soon as possible.

[3] Author to whom any correspondence should be addressed.

The major significance of using the precision level as a precision machine is to discover Abbe errors [15, 16]. According to the Abbe principle, if the measuring axis is not in line with the functional axis, the angular errors of the moving stage will be enlarged by the factor of the offset and result in positioning error of the stage motion. Cumulating all linear and angular errors will lead to volumetric errors in the working zone [17, 18].

In this paper, a dual-axis precision level is designed and its working model based on the double-layer pendulum principle and commercial DVD pickup head technology is studied. In order to achieve quick settling time of the swinging mechanism, proper viscous fluid is filled to create a damping effect. Although the DVD pickup head is based on the astigmatic principle for focusing measurement [19], it can be used as an autocollimator for dual-angle measurement if the front objective lens is removed [12, 20–23]. Instead of using the DVD pickup head, Professor Gao developed a series of micro-angle sensors using a laser diode and a similar optical principle to measure surface profiles [24–26]. This paper is structured as follows: section 2 introduces the principle of angle measurement of the DVD pickup head; section 3 analyzes the mechanical system design of the dual-axis precision level; section 4 reports the calibration method and results; section 5 presents some application examples on precision machines and the conclusion is given in section 6.

2. Principle of angle measurement of the DVD pickup head

In this research, a Hitachi HOP-1000 DVD pick-up head is modified by removing the grating, objective lens and the voice coil motor (VCM) so as to output with a collimated laser beam, as shown in figure 1. Initially, a laser diode generates a beam of light of linear polarization, say P-polarization, at a divergent angle, which passes through a polarizing plate beamsplitter (PBS) and reflects to a quarter waveplate (QWP). The linearly polarizing state of the beam will change to a circularly polarizing state. After it passes through a collimating lens, the beam will become a parallel light and return along the same path after it is reflected from a plane mirror. This returned beam will change to S-polarization after it passes through the QWP again. The PBS allows the beam only to transmit through to the correcting cylindrical lens and project it onto the four-quadrant photodiode (PDIC). The spot on the PDIC is a circular shape (about 80 μm in diameter), as can be seen on the enlarged image taken by a camera. According to the principle of optical autocollimator, the tilted angle (θ) of the plane mirror will result in the focused spot being shifted laterally by $2f\theta$, where f is the focal length of the collimator [1]. The built-in four-quadrant photodiode is used as the beam spot position detector to detect the amount of spot shift. The two tilted angles of the plane mirror can then be calculated. To ensure that the laser beam will not fluctuate with ambient temperature, a power supply in association with an automated power controller (APC) circuit is used to stabilize the output power.

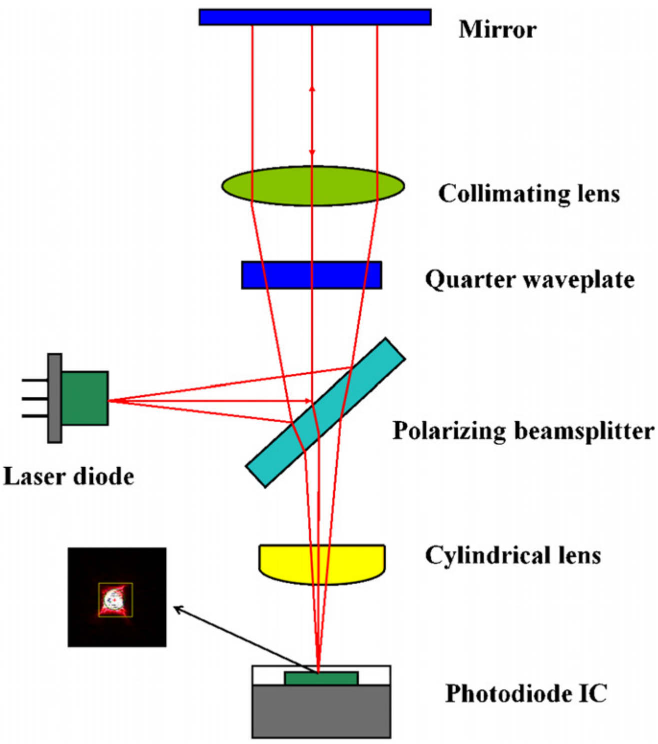


Figure 1. The configuration of a DVD autocollimator.

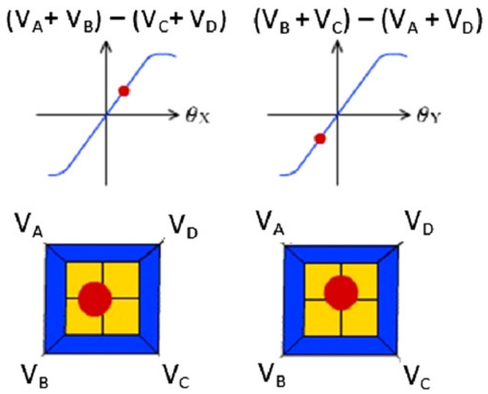


Figure 2. The relationship between the location of beam spot and voltages (left: yaw, right: pitch).

Through the current-to-voltage converter with proper resistance, the photocurrent transformed from the photodiode will be converted to voltage for further operation. According to the location of the reflected beam projected onto the four quadrant photodiode, the corresponding voltages to the yaw angle (θ_y) and the pitch angle (θ_x) can be expressed by the following equations, as shown in figure 2:

$$\theta_x = (V_A + V_B) - (V_C + V_D) \tag{1}$$

$$\theta_y = (V_B + V_C) - (V_A + V_D)\,. \tag{2}$$

Therefore, the angular errors (pitch and yaw) can be measured by the DVD pick-up head based on the autocollimator principle.

As for signal processing, the analog voltages of the four quadrants are amplified by the differential amplifier

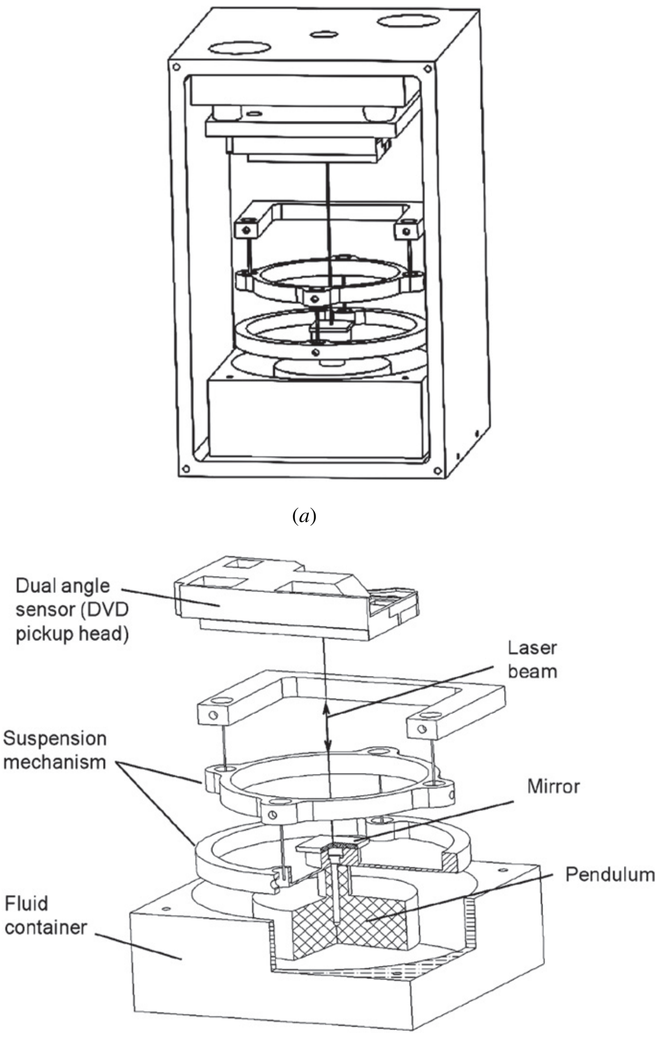


Figure 3. The overall structure of the DVD level. (*a*) Assembled structure of the dual-axis level. (*b*) Functional components.

circuit and acquired by the microprocessor (AVR) through the analog-to-digital converter (ADC). After being computed by equations (1) and (2), the angular errors can be obtained and shown on the LCD display or output to a PC by RS-232 as an angle monitoring system.

3. Design of the level mechanism and its mechanical system

3.1. Mechanical design

In this study, the design of the dual-axis optoelectronic level is developed based on the two-layer suspension mechanism that provides two angular swings relative to the gravitation. The overall 3D structure packaged in a case is shown in figure 3(*a*), and its individual components are illustrated in figure 3(*b*). A pendulum, made of stainless steel, is suspended from the upper suspension ring by two parallel wires in one plane. The upper ring is suspended by two wires in another orthogonal plane from the top frame. The fixed point of each wire on the upper supporting body is the pivot point of the stretched wire. The geometrical structure of this two-layer suspension mechanism is similar to the leaf spring parallelogram. A detailed illustration in figure 4 shows that the upper ring is sensitive only to the swing along the *X*-axis, called the yaw angle θ_x, and the pendulum is sensitive only to the *Y*-axis, called the pitch angle θ_y, as shown in figure 5. The DVD autocollimator is mounted on the top frame and is faced down. The laser beam will reflect from the mirror, which is mounted on the top of the pendulum. The pendulum is immersed in the base container which is filled with viscous fluid serving as a damper for this angular vibration system.

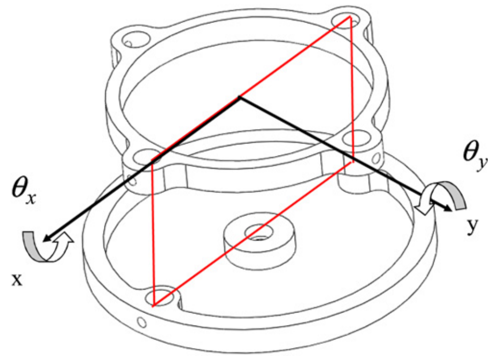


Figure 4. The two-layer suspension mechanism.

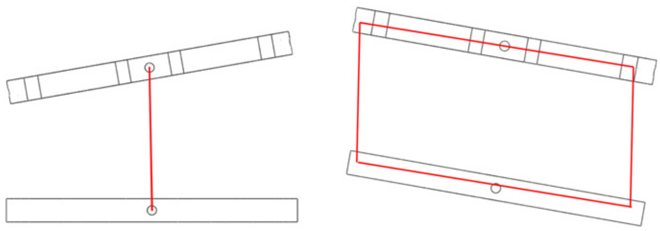


Figure 5. (*a*) The yaw swing. (*b*) The pitch swing.

3.2. Analysis of the mechanical system

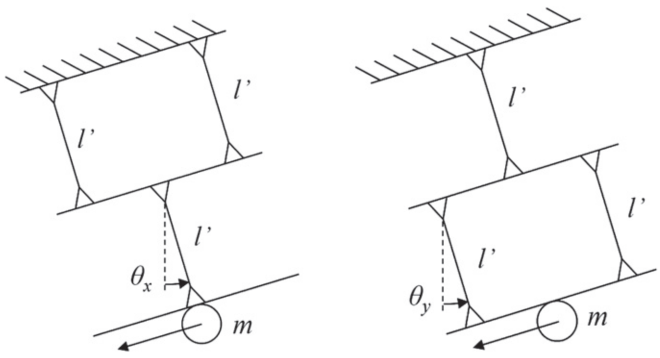
According to the designed dual-angle small vibration system, when the level tilts a small angle of θ_x or θ_y, the motion of the pendulum can be expressed as shown in figure 6(*a*) or (*b*), respectively. During the pendulum oscillation, all the strings will be pulled by the centrifugal force of the pendulum and move together as a rigid body. Therefore, from either the *X* view or *Y* view, the oscillation model can be simplified to one pendulum system, as shown in figure 7, based on which the theoretical analysis can be obtained.

The equivalent mass-damping mechanical system and its free-body diagram can be seen in figure 8. When the pendulum is swung by a small angle θ, the moving mass is under a gravitational force (mg) and a tensile force of string (T). The motion equation can be expressed by

$$ml^2\ddot{\theta} + cl^2\dot{\theta} + mgl\sin\theta = 0. \tag{3}$$

According to the small angle assumption it can be simplified to

$$\ddot{\theta} + \frac{c}{m}\dot{\theta} + \frac{g}{l}\theta = 0, \tag{4}$$



(*a*) (*b*)

Figure 6. Equivalent mechanical system: (*a*) swing of θ_x and (*b*) swing of θ_y.

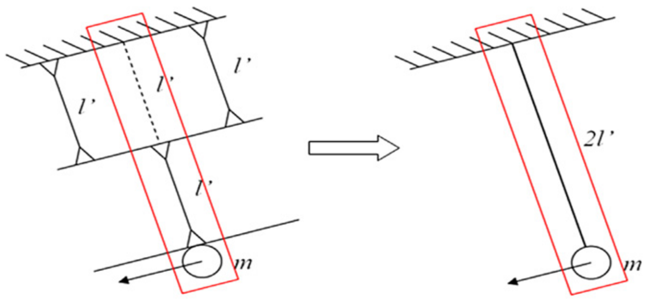
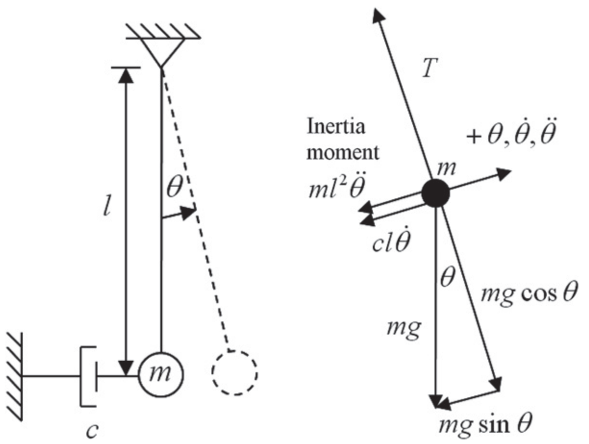


Figure 7. The simplified model of a two-layer pendulum system.



(*a*) (*b*)

Figure 8. (*a*) Simplified mechanical system. (*b*) Equivalent free-body diagram.

where g is the gravitational acceleration, l is the length of the string, c is the damping coefficient and m is the mass of the pendulum. Through Stokes' law [27], the damping coefficient c can be obtained by equation (5). Moreover, the mass is expressed by equation (6):

$$c = 6\pi\mu r \tag{5}$$

$$m = \frac{4\pi r^3}{3} \times \rho, \tag{6}$$

where μ is the viscosity of liquid, r is the radius and ρ is the density of the pendulum. In this design, we used glycerol as the damping liquid and a steel ball as the pendulum. Table 1 shows the parameter list used in this system.

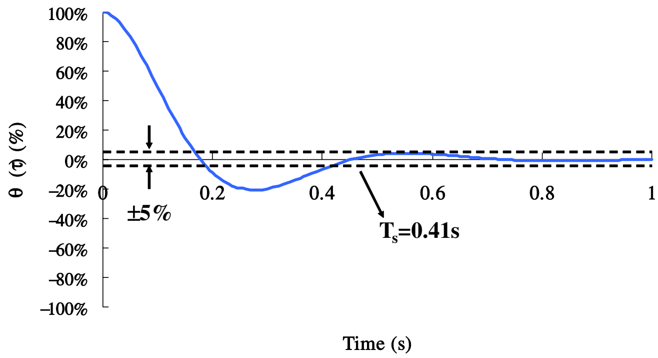


Figure 9. Time response and settling time of the level.

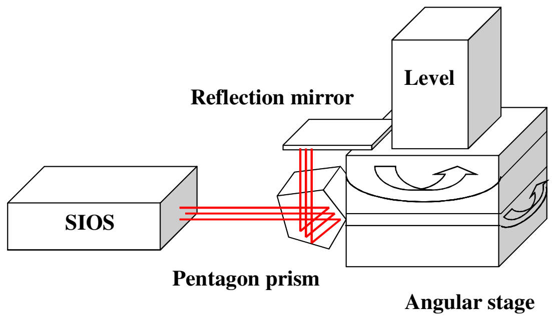


Figure 10. Setup for calibration of the DVD level.

Table 1. Parameters of the level.

μ	r	ρ	g	l
1.5 N s m^{-2}	8 mm	7850 kg m^{-3}	9.81 m s^{-2}	6 cm

Substituting the parameters into equations (5) and (6) and giving an initial condition in equation (4), the equation of motion is solved by equation (7). The time response behavior of this pendulum oscillation system is plotted in figure 9. The settling time [28] is within 0.5 s which is faster than other commercial levels (normally about 1 s):

$$\theta(t) = e^{-5.73t}(\cos 111.43t + 0.501 \sin 11.43t). \tag{7}$$

4. System calibration

The setup for calibration of the dual-axis DVD level is shown in figure 10. The DVD level and the mirror are mounted on the dual-axis precision rotary stage. The SIOS-2000 Triple Beam Interferometer was used as the reference to compare with the level readings in pitch and yaw. The pentaprism was to bend the laser beam upward by 90°. Calibrated results can be represented by the best-fit linear relationship, as shown in figures 11 and 12 with respect to roll and pitch angles respectively. It can be seen that the accuracy of the level is better than ±0.7 arcsec with a range of ±30 arcsec for both angles. It is also noted that looking from earth this roll motion is the same as the yaw motion if looking from the DVD pickup head as mentioned in figure 3.

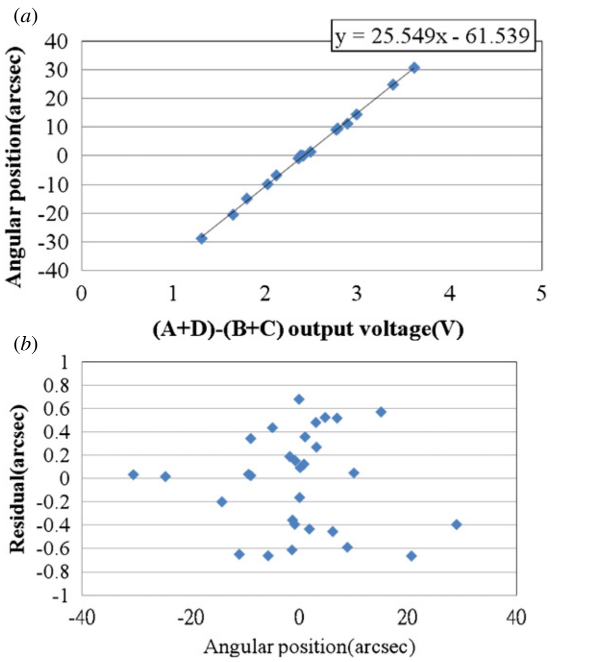


Figure 11. (*a*) Best fit of roll angle calibration. (*b*) Residual errors of roll angle calibration.

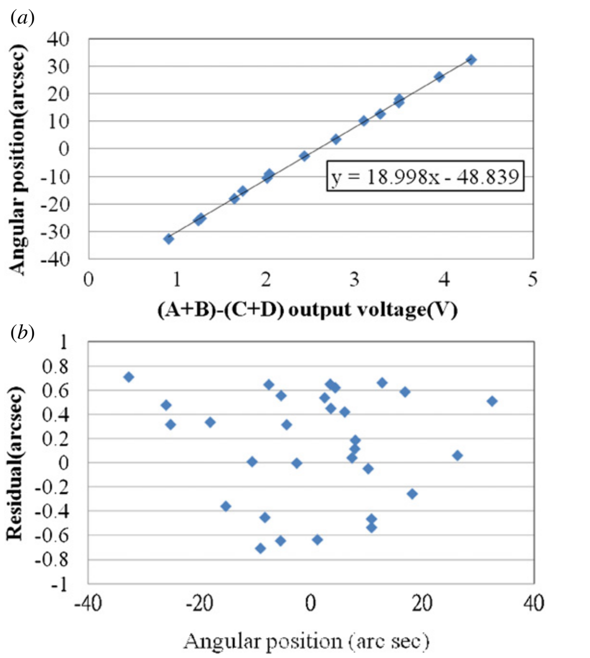


Figure 12. (*a*) Best fit of pitch angle calibration. (*b*) Residual errors of pitch angle calibration.

5. Applications

5.1. Angular measurement of a CNC milling machine

In the first experiment, the dual-axis optoelectronic level was used to measure the pitch and roll angular errors of a CNC milling machine. The experimental setup on the CNC machine tool is shown in figure 13. The developed dual-axis level is placed on the work table. The pitch angle during the table motion is measured by the level and compared with an HP

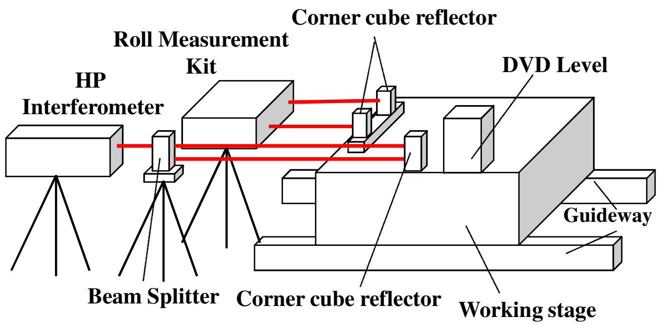


Figure 13. Experimental setup on a CNC milling machine.

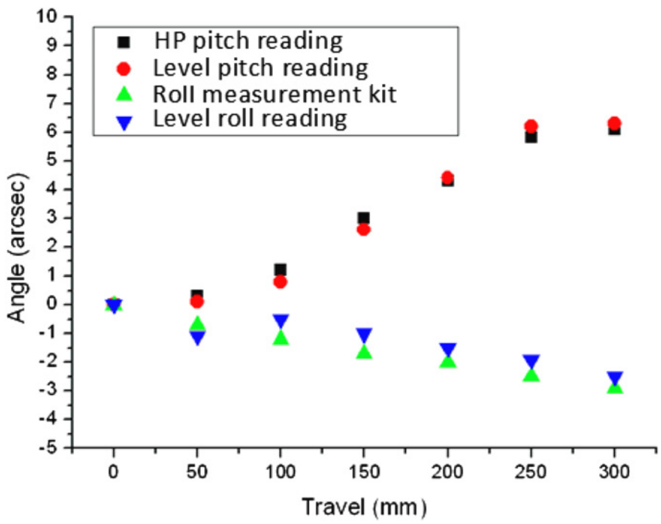


Figure 14. Measured angular errors of the CNC milling machine.

5529A Angular Interferometer. To compare with the roll angle measurement of the level, a parallel vertical straightness measuring kit, composed of two sets of laser source, corner cube retro reflector and quadrant detector, has been developed [29] which is modified from our previous 6-dof measuring system [30]. The compared results for pitch and roll errors are quite consistent, as shown in figure 14.

5.2. Angular measurement of a coordinate measuring machine

In the second experiment, the angular measurement setup for a gantry coordinate measuring machine (CMM) in Metal Industries Research & Development Centre (MIRDC) is shown in figure 15. The DVD level was installed on the table for the measurement of the two angles. The pitch angle was compared with a Renishaw ML-10 Interferometer. Figure 16 shows the pitch angular errors of the moving table. The relative error is within 1 arcsec, which demonstrates the applicability of the developed dual-axis electronic level.

It has to be mentioned here that experiment 1 was carried out at the first author's lab while experiment 2 was carried at the last author's lab. The two labs are separated by about 200 km. In transport, the instrument is best placed vertically

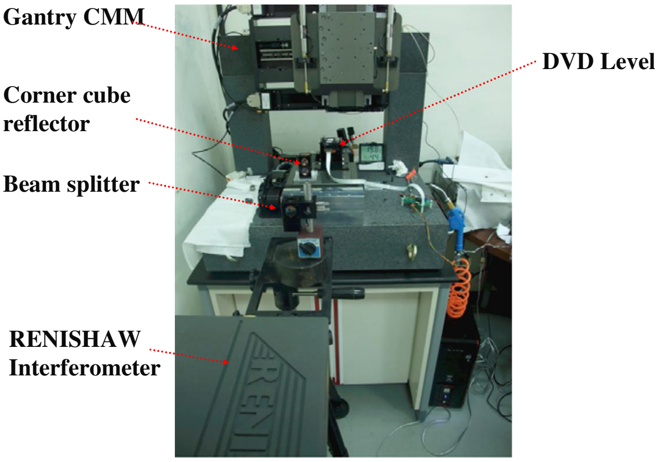


Figure 15. Experimental setup on a gantry CMM.

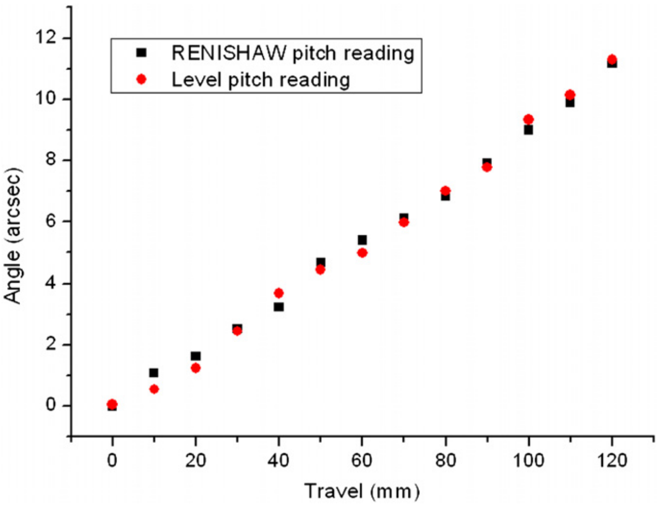


Figure 16. Measured pitch errors of the gantry CMM.

so that the damping fluid will not flow out. In practice, we put a flexible PE film to seal the opening gap between the fluid container and the pendulum. A small tilt of the instrument will not affect its accuracy.

6. Conclusions

This paper has presented the design and its working model of a dual-axis opto-electronic level with low cost and high precision. The system is based on a commercial DVD pickup head and the mechanism of the pendulum. In combination with a microprocessor for data acquisition, the angular errors of axis motion can be measured and shown on the LCD display or output to a PC by RS-232 as an angle monitoring system. As to accuracy, the error of the dual-axis optoelectronic level is better than ±0.7 arcsec in the measuring range of ±30 arcsec of each axis, and the stabilized time is within 0.5 s. Experimental results show the applicability of this instrument in industry.

References

[1] Galyer J F W and Shotbolt C R 1990 *Metrology for Engineers* 5th edn (London: Cassell)
[2] British Standard 2008 Specification for surface plates BS817
[3] Ali A F 1987 An experiment on the precision of engineering levels *Aust. Surv.* **33** 731–3
[4] ISO 1996 Test code for machine tools: part 1. Geometric accuracy of machines operating under no-load or finishing conditions ISO 230-1
[5] Agilent Technologies 2000 Agilent 5529: A Dynamic Calibrator
[6] Chang P and Olemenn B 2010 Joint-angle measurement using accelerometers and gyroscopes—a survey *IEEE Trans. Instrum. Meas.* **59** 404–14
[7] Khiat A, Lamarque F, Prelle, Bencheikh C N and Dupont E 2010 High-resolution fibre-optic sensor for angular displacement measurements *Meas. Sci. Technol.* **21** 025306
[8] Kim D H 2009 A fiber-optic tiltmeter system based on the moiré-fringe effect *Meas. Sci. Technol.* **20** 025203
[9] Wyler A G 1977 Device for measuring accelerations, particularly accelerations due to gravity *US Patent Specification* 4023413 http://www.wylerag.com
[10] Talyvel, Taylor-Hobson Co. http://www.taylor-hobson.com/
[11] Brook Automation Co. High resolution electronic level wafer EL-3003 user manual http://www.brooks.com/pages/803_alignment_calibration.cfm
[12] Perchat R M and Mccarty R G 2007 Multi-axis bubble vial device *US Patent* 7497021
[13] Chu C L, Lin C H and Fan K C 2007 Two-dimensional optical accelerometer based on commercial DVD pick-up head *Meas. Sci. Technol.* **18** 265–74
[14] Jywe W Y and Chen C J 2006 The development of a novel optoelectronic level *Mater. Sci. Forum* **505–507** 247–52
[15] Bryan J B 1979 Abbe principle revisited–updated interpretation *Precis. Eng.* **1** 129–32
[16] Bryan J B and Carter D L 1979 Design of a new error-corrected coordinate measuring machine *Precis. Eng.* **1** 125–8
[17] Fan K C 1989 Generalized study of volumetric error analysis for NC machine tools and CMMS, part one—mathematical model *J. Chin. Soc. Mech. Eng.* **10** 135–44
[18] Fan K C 1989 Generalized study of volumetric error analysis for machine tools and CMMS, part two—applications *J. Chin. Soc. Mech. Eng.* **10** 145–52
[19] Fan K C, Lin C Y and Shyu L H 2000 Development of a low-cost focusing probe for profile measurement *Meas. Sci. Technol.* **11** N1–7
[20] Armstrong T R and Fitzgerald M P 1992 An autocollimator based on the laser head of a compact-disk player *Meas. Sci. Technol.* **3** 1072–6
[21] Liu Y C, Fan K C, Chu C L, Werner C and Jaeger G 2008 Development of an optical accelerometer for low frequency vibration using the voice coil on DVD pickup head *Meas. Sci. Technol.* **19** 084012
[22] Hwu E-T, Hung S-K, Yang C-W, Hwang I-S and Huang K-Y 2007 Simultaneous detection of translational and angular displacements of micromachined elements *Appl. Phys. Lett.* **91** 221908
[23] Huang H-L, Liu C-H, Jywe W-Y, Wang M-S, Jeng Y-R, Duan L-L and Hsu T-H 2009 Development of a DVD pickup-based four-degrees-of-freedom motion error measuring system for a single-axis linear moving platform *Proc. Inst. Mech. Eng.* B **224** 37–50
[24] Gao W, Ohnuma T, Satoh H, Shimizu H and Kiyono S 2004 A precision angle sensor using a multi-cell photodiode array *Ann. CIRP* **53** 425–8

[25] Saito Y, Arai Y and Gao W 2009 Detection of three-axis angles by an optical sensor *Sensors Actuators* A **150** 175–83
[26] Saito Y, Arai Y and Gao W 2010 Investigation of an optical sensor for small tilt angle detection of a precision linear stage *Meas. Sci. Technol.* **21** 054006
[27] Stokes G G 1851 On the effect of the internal friction of fluids on the motion of pendulums *Trans. Camb. Phil. Soc.* **9** 8–106
[28] Nise N S 2004 *Control Systems Engineering* 4th edn (New York: Wiley)
[29] Lin S Y 2010 Development and applications of multi-degree-of-freedom angular error measurement system *Master Thesis* National Taiwan University
[30] Fan K C and Chen M J 2000 A six-degree-of-freedom measurement system for the accuracy of *X*–*Y* stage *Precis. Eng.* **24** 15–23