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2013 Meas. Sci. Technol. 24 035902

(http://iopscience.iop.org/0957-0233/24/3/035902)

IOP Publishing — Measurement Science and Technology
Meas. Sci. Technol. **24** (2013) 035902 (6pp) doi:10.1088/0957-0233/24/3/035902

A novel dual-axis optoelectronic level with refraction principle

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Received 2 October 2012, in final form 22 November 2012
Published 4 February 2013
Online at stacks.iop.org/MST/24/035902

Abstract
Levels are fundamental metrological tools for machine leveling and angle measurements. Current levels are all based on the pendulum principle and bubble vial principle. The former is precise but complicated, while the latter is not precise enough. This paper presents a novel, simple and precise optoelectronic level. It is based on the principle of light refraction in the transparent and viscous fluid. The fluid surface is always in leveling condition regardless whether the ground is level or not. Measuring the refraction angle with precise dual-axis autocollimator can directly reflect the inclined angle of the level. A leakage prevention design is also proposed to allow the level to be placed in any pose. Calibrated by an angular interferometer, the error of the dual-axis optoelectronic level is better than ± 0.7 arcsec in the measuring range of ± 100 arcsec, and better than ± 0.4 arcsec for the range of ± 30 arcsec, for both axes. Without the need of a pendulum mechanism, this is a simpler design for precision level.

Keywords: optoelectronic level, light refraction, autocollimator, angle measurements

(Some figures may appear in colour only in the online journal)

1. Introduction

A precision engineering level is a very fundamental metrological tool for absolute angle measurement of out of earth level. It is frequently applied to machine bed leveling to 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]. 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, such as the capacitive sensor used in the Leveltronic of Wyler Co. [5], the inductive sensor used in the Talyvel of Taylor Hobson Co. [6] and other sensors [7, 8]. However, all these precision levels are only in one axis. Repeated changing from one axis to the other is inevitable when applying the one-axis level to 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 be read precisely from its bubble displacement on the 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 US patents 7497021 [9] and 5313713 [10]. Other bubble vial types use electrolytic bulb [11], electrode potentiometer [12] and ferromagnetic fluid [13] to sense the swing of the filled fluid, but the resolution and accuracy are not as good as the pendulum type. Most applications of bubble type levels are for larger angles with lower resolution, such as in building construction like the inclinometers. Jywe *et al* developed a pendulum type dual-axis optoelectronic level but lack of damper design [14]. The author's group also developed a pendulum type dual-axis optoelectronic level [15], but the double-layer suspension mechanism makes the structure quite complicated.

It is known that all electronic levels require a filling of viscous fluid for quick damping. Either with the aid of a pendulum or conductive material, it is simply for the measurement of out of gravity. By nature, the fluid motion can

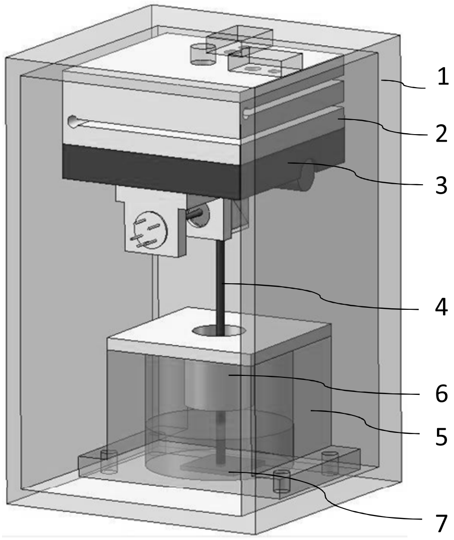


Figure 1. Assembled structure of dual-axis level containing: (1) frame, (2) adjustable mechanism, (3) optical module, (4) laser beam, (5) container, (6) leakage prevention tube and (7) plane mirror.

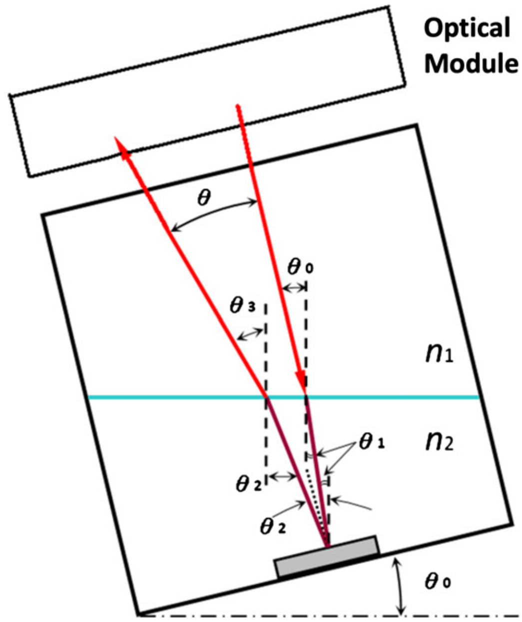


Figure 2. Optical path of the laser beam due to light refraction.

directly reflect the inclined angle to the earth level, because the fluid surface always remains level. Instead of measuring the swing of the pendulum to the gravity, sensing the change of the fluid surface angle to the gravity is a simpler way.

In this paper, a novel dual-axis precision level is proposed based on the light refraction principle. The emitted light will be refracted if the incident angle is changed. Measuring the change of angles between the input and output light beams can directly relate to the angle of the level. A precision optical pickup head based on the principle of an autocollimator is designed and is proved to have better accuracy than the DVD pickup head that the author's group used previously [15]. This paper is structured as follows: section 2 introduces the structure design of the proposed level; section 3 analyzes the induced angle of the laser beam based on the principle of light refraction; section 4 introduces the design of a miniature autocollimator embedded in the level system; section 5 describes the leakage prevention design; section 6 reports the calibration method results and the conclusion is given in section 7.

2. Structure design of the refraction type level

The structural design of this pendulum-free precision level is shown in figure 1. An optical module based on the autocollimator principle is the main sensing device. It emits a laser beam, with the angle adjustable by a flexure hinge type dual-axis mechanism, normal to the fluid surface when the level is placed on a leveled surface. The fluid is filled to a certain height in a container that is mounted on the base plane of the level frame. There is a refraction angle of the laser beam in the fluid when the incident laser beam is not normal to the fluid surface. A plane mirror mounted on the bottom surface inside the container will reflect the beam back to the fluid surface, through which the beam will be refracted again when it transmits out to the optical module. The angle difference between the emitted beam and the received beam can be detected by the optical module. When the level is placed on an inclined surface, the surface angle is related to the angle difference in the optical module. The fluid can be settled into steady-state condition due to the damping effect of its viscosity. The level is normally used as a portable instrument. A leakage prevention tube is particularly designed to avoid the fluid flowing out when the level is placed in any pose. Such a level design is very simple without the need of a pendulum mechanism or any conductive material to sense the swing angle of the fluid or the level body. Details of the refraction effect and the optical module will be explained in the following sections.

3. Principle of light refraction in the level

Refraction is a natural phenomenon when the light passes through different media. The optical path of the level system is illustrated in figure 2. The laser beam emitted from the optical module is initially in the air with refractive index n_1 (=1) and adjusted to normal to the fluid surface when the level is placed on a leveled ground. When the ground has an inclined angle of θ_0, the fluid surface is still leveled by nature. A refraction angle of θ_1 of the laser beam transmitted to the fluid will appear by Snell's law:

$$n_1 \sin\theta_0 = n_2 \sin\theta_1, \quad (1)$$

where n_2 is the refractive index of the fluid. With the light reflection on the bottom plane mirror, the emitted angle of the reflected laser beam back to the fluid surface will be θ_2 expressed by

$$\theta_2 = 2\theta_0 - \theta_1. \quad (2)$$

The output refracted angle of the laser beam out of the fluid surface will then be θ_3 expressed by

$$\theta_3 = \sin^{-1}\left(\frac{n_2 \sin\theta_2}{n_1}\right). \quad (3)$$

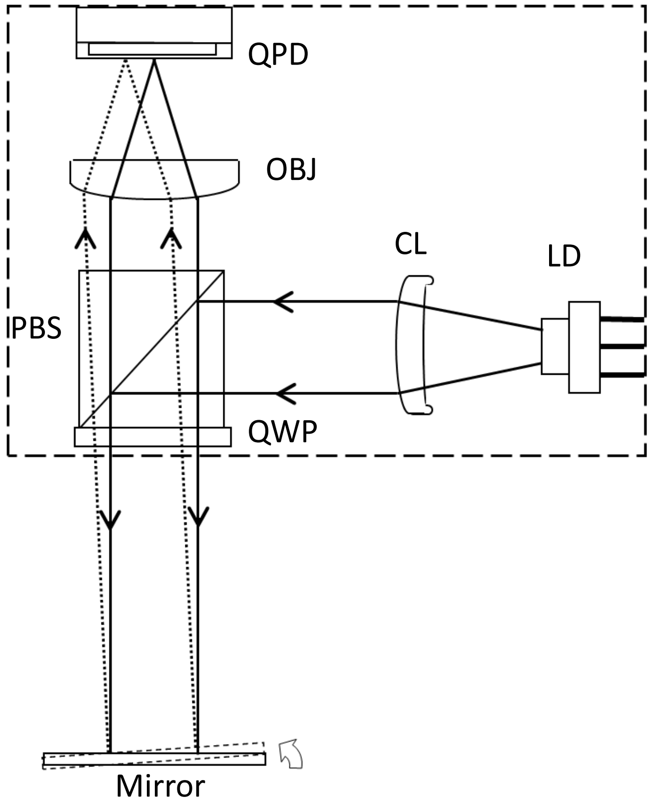


Figure 3. The principle of autocollimator design.

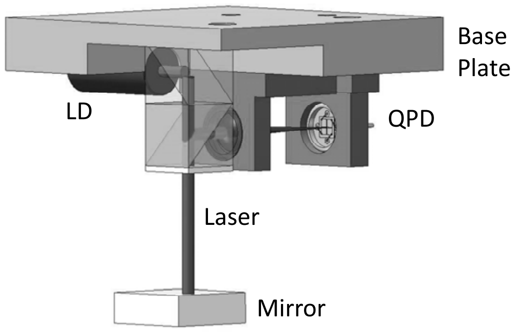


Figure 4. The physical design of autocollimator.

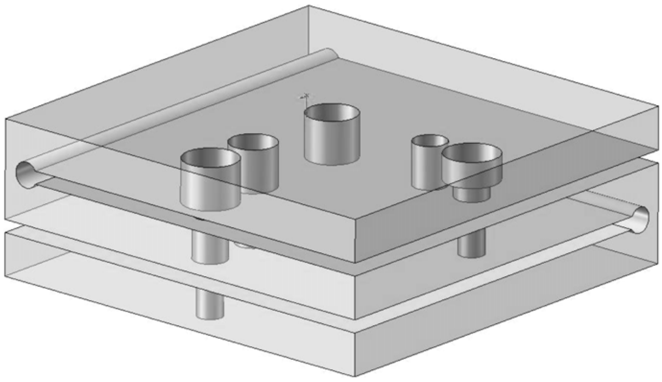


Figure 5. The hinge type adjustable mechanism.

The angle difference of the emitted beam and the returned beam detected by the optical module will be θ, which is the subtraction of θ_0 from θ_3. Therefore, the angle of the level is $\theta_0 = \theta_3 - \theta$. In practice, the measurement range of the precision level is normally very small. Combining equations (1) to (3), the level angle can be simplified to

$$\theta_0 = \theta_3 - \theta = \frac{n_1\theta}{2(n_2 - n_1)}. \tag{4}$$

It is clearly seen that the actual inclined angle of the level is proportional to the angle measured by the optical module.

4. Design of the optical module

The purpose of the optical module is to measure the change of angles of emitted and received laser beams in two axes normal to the laser beam direction. This is the same principle as the autocollimator. Although there has been some research that modified the DVD pickup head to perform angle measurements for various purposes, such as [16–18] and the author's previous reports [19, 20], the embedded sensor (four quadrant photodetector) has too small an active area and high noise due to mass production and low cost. This research gave up this choice and redesigned a flat type miniature autocollimator to meet the requirements of precision, small size and low cost of the level. The principle of the autocollimator is well known in the metrology field. Gao *et al* developed a series of precision angle sensors using a similar optical principle [21, 22]. The optical system of the designed autocollimator is shown in figure 3. A divergent laser beam output from a laser diode (LD) can be collimated to a parallel beam through a collimating lens (CL). Reflected by a polarizing beam splitter (PBS) and passed through a quarter waveplate (QWP), the beam will change to the circularly polarizing state. The reflected beam from the plane mirror will change to linear polarization when it passes through the QWP again and transmits through the PBS. The objective lens (OBJ) will then focus the beam to the surface of the quadrant photodetector (QPD), which can detect two inclined angles from the normal based on the principle of the autocollimator. The physical design conforming to this principle is shown in figure 4. All optical components are mounted on a flat base plate, which is fixed to the adjustable flexure hinge mechanism, as shown in figure 1, so that the angles of the emitted laser beam can be fine tuned in two directions. Figure 5 shows the design of the adjustable mechanism, which is a monolithic hinge type single block fabricated by the wire EDM process. Although there are some commercial spring type dual-axis adjustable tables, the angle locking is not permanent enough due to the spring release effect. This is the reason why the hinge-type mechanism is selected in this study. From long-term tests the spot position is very stable.

5. The leakage prevention design

A level is often used as a portable instrument. Even if put in a carrying case for transportation, the level will be left in any pose. Without the top cover of the container, the fluid will easily flow out. Although putting a transparent glass, such as the sapphire glass, can seal the fluid, it still has a small amount

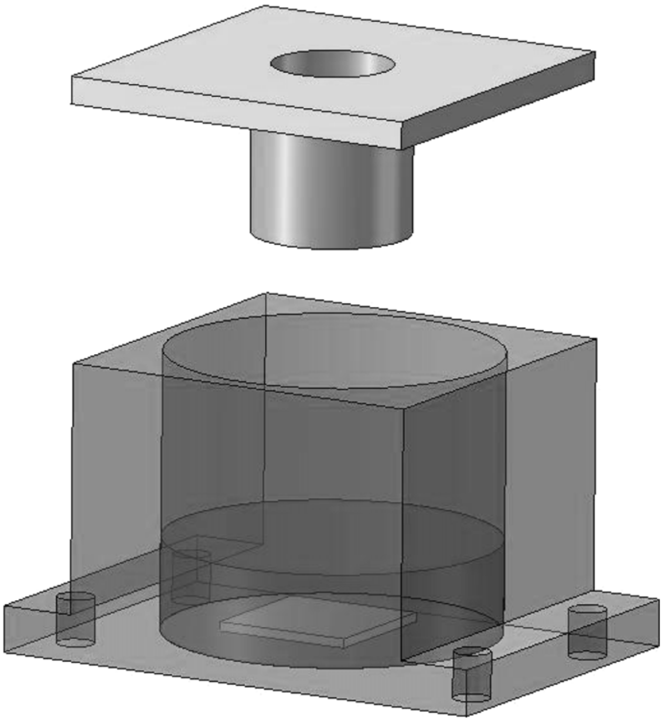


Figure 6. The leakage prevention design of top cover.

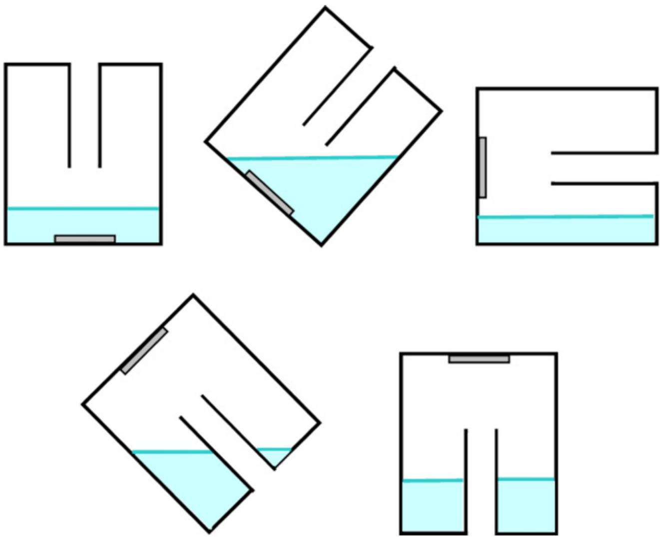


Figure 7. The level tilted in different directions.

of light reflection that will produce parasitic interference on the quadrant photodetector. Moreover, light refraction through the glass twice will produce a nonlinear effect on the sensor. A special design to prevent the fluid leakage is thus proposed in this work. As shown in figure 6, a hollow cover plate with an extruded tube is placed on the top of the container. The laser beam can pass through the tube without affecting the linear relationship of equation (4). The bottom of the tube is higher than the fluid level. With any tilted position of the level, the tube can block the fluid from flowing out of the container, as schematically shown in figure 7. It is noted here that the fluid is a viscous material with low evaporation rate and the level is

Figure 8. Prototype of the refraction type level.

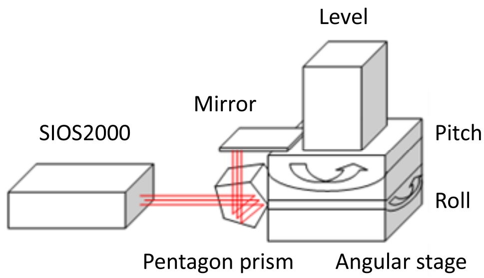
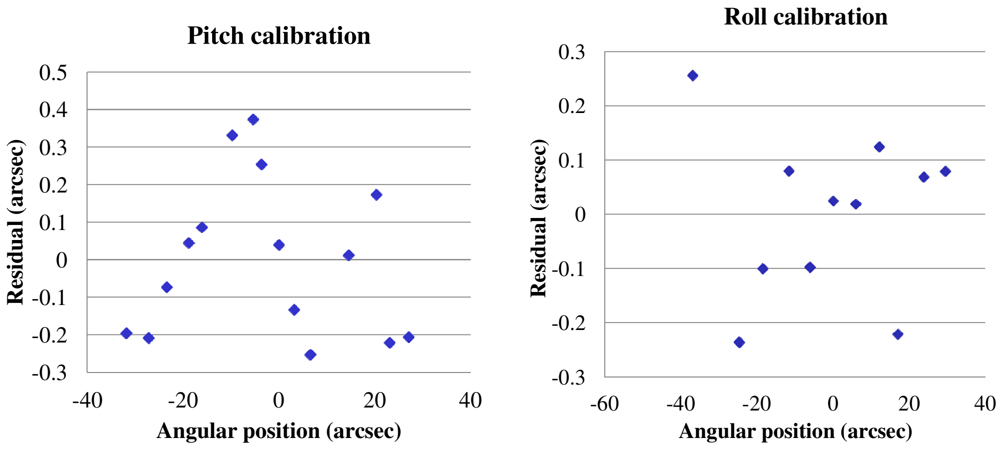


Figure 9. Setup for calibration.

sealed by the outside frame. Even if there is a small evaporation of the fluid within the frame, the effect will be saturated and the fluid height does not affect the angle measurement.

6. System calibration

Figure 8 shows the prototype of the designed level. The fluid used is silicon oil with refraction index $n_2 = 1.52$, as provided by the vendor. The setup for calibration of dual-axis precision level is shown in figure 9. The level and the mirror are mounted on a dual-axis precision angle adjustable stage in pitch and roll. A SIOS-2000 Triple Beam Interferometer was used as the reference to compare with the level readings in two directions. Since the detected refraction angle is proportional to the inclined angle of the level, the calibrated results can be best-fitted by a least-squares line. Although the level can have large measuring range, however, most precision tables or stages do possess very good flatness or angular errors. The calibration, therefore, conducted two measuring ranges, i.e. ± 30 arcsec and ± 100 arcsec. Figure 10 shows the residuals of small



(*a*) (*b*)

Figure 10. Residuals of ±30 arcsec range calibration: (*a*) pitch and (*b*) roll.

Table 1. Five times of pitch error calibration (unit: arcsec).

Angle	1	2	3	4	5	Avg.	$2\sigma_{n-1}$
100	−0.7	−0.1	−0.3	−0.1	0.3	−0.18	0.73
80	−0.4	−0.9	0.4	−0.6	−0.5	−0.4	0.97
60	−0.4	0.5	0.6	0.6	−0.5	0.16	1.12
40	0.1	0.5	0.2	0.7	−0.4	0.22	0.84
20	−0.4	−0.5	−0.4	0.2	−0.4	−0.3	0.57
−20	−1	0.2	−0.5	−0.2	−0.8	−0.46	0.95
−40	−0.4	−0.6	0.1	0.1	−0.5	−0.26	0.67
−60	0.4	−0.3	0.3	0.2	0.9	0.3	0.86
−80	0.6	0.6	0.7	0.9	0.7	0.7	0.24
−100	0.7	−0.1	0.8	0.7	0.6	0.54	0.73

Table 2. Five times of roll error calibration (unit: arcsec).

Angle	1	2	3	4	5	Avg.	$2\sigma_{n-1}$
100	0.5	0.5	0.2	0.8	1.1	0.62	0.68
80	0.2	−0.1	0.3	0.5	0.7	0.32	0.61
60	−0.5	0.1	0.5	0.3	0.6	0.2	0.87
40	−0.6	−0.4	−0.3	0	0.5	−0.16	0.86
20	−0.4	−0.3	−0.3	0.2	0.6	−0.04	0.86
−20	0.6	−0.5	0.6	−0.1	0.6	0.24	1.03
−40	0.1	−0.3	−0.1	−0.3	0.3	−0.06	0.52
−60	−0.2	−0.6	−0.1	−0.4	0.3	−0.2	0.68
−80	−0.5	−0.9	−0.3	−0.6	−0.2	−0.5	0.55
−100	−0.4	−0.5	−0.4	−0.3	−0.1	−0.34	0.30

range calibration. It is shown that systematic accuracy can be achieved within ±0.4 arcsec. For the long-range calibration, each axis was carried out five times and the results of pitch and roll errors are listed in tables 1 and 2, respectively. The average error is better than ±0.7 arcsec and the uncertainty (95% confidence level) is within ±1.1 arcsec within a range of ±100 arcsec. This performance is superior to the pendulum-type levels in the market and our previous design.

It has to be pointed that there will be more or less cross-talk between two axes due to the alignment error of the level's coordinate and the SIOS interferometer's coordinate, if the dual axes calibration procedures are conducted separately. Figure 11 shows the average cross-talk effect of the conducted

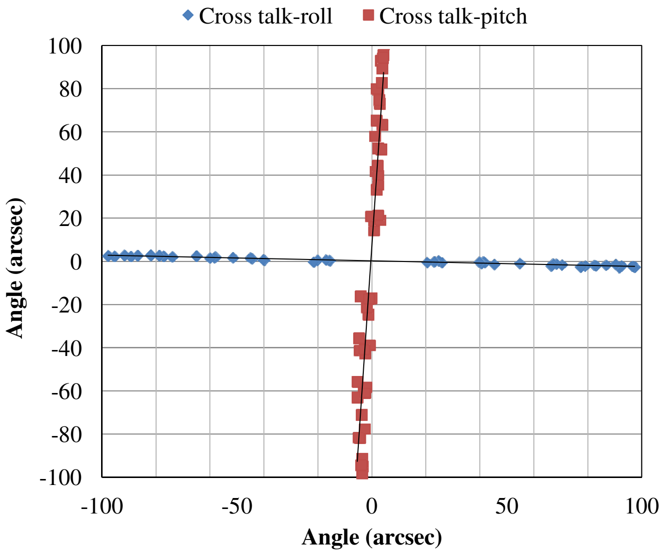


Figure 11. Cross-talk experiment of two axes.

five times long-range calibration. In such a case, the coordinate rotational transformation operation has to be applied to compensate the alignment error. This report emphasizes the feasible design of the refraction-type precision level. Details of cross-error compensation are not described here.

For any instrument design, the settling time and the long-term stability are also of interest. The settling time of this pure fluid level is varied with the parameters of fluid viscosity, inner diameter of container and fluid height. The viscosity of adopted silicon oil is about 1000 centistokes as provided by the vendor. Several different heights of the fluid level were tested and it was found that the higher the fluid surface is, the shorter the settling time will be. The fluid height, however, has an upper limit in order to avoid flowing out when the level is tilted, as described in section 5. With the proper selection of the container dimension and the fluid height in this study, the experimental settling time is plotted in figure 12. It is found that the settling time elapses about 3 s if the level is slightly moved. Figure 13 shows the long-term stability test. For a duration of 30 min, the signal drifts less than

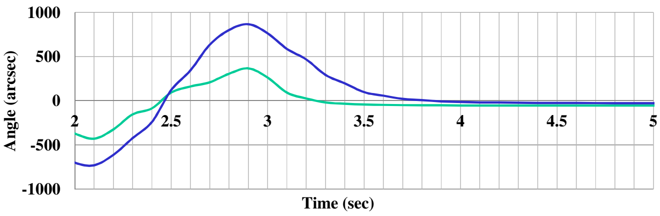


Figure 12. Settling time test.

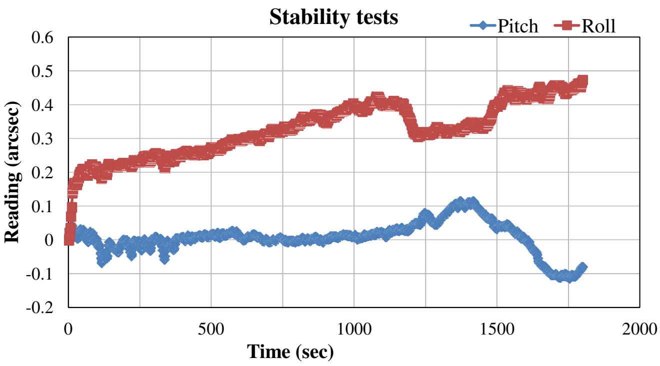


Figure 13. Long-term stability test.

0.5 arcsec. Current results are only to explore the phenomenon and validate the feasibility of the proposed level based on the refraction principle. More efforts have to be made to improve the functions for future commercialization.

7. Conclusions

This paper presents a new design methodology of the dual-axis precision level. Based on the principle of light refraction, an embedded autocollimator can detect refracted angles of the laser beam in two directions. The specially designed miniature autocollimator shows better performance than the DVD type angle sensor. Calibrated results show that for a large range of ± 100 arcsec the accuracy is within ± 0.7 arcsec with ± 1.1 arcsec uncertainty, and for small range of ± 30 arcsec the accuracy is within ± 0.4 arcsec, for both axes. With the aid of the leakage-free cover structure on the container, the filled-in fluid will not flow out at any pose of the level. This is advantageous for carrying out field service. This pendulum-free novel level is simpler in structure, lower in cost and higher in accuracy in comparison with commercial pendulum-type levels. It is suitable for precision level alignment of any machine and precision measurement of dual-axis angular errors of any moving stage. This study validates the feasibility of the proposed level. The settling time can be further reduced by selecting better parameters, such as the fluid viscosity, the fluid height and its cross-sectional area. In practice, the cross-talk error caused by misalignment error during assembly should be compensated either by fine adjusting mechanism or by software.

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