Research on Method of Photoelectric Measurement for Tilt Angle of Scanning Mirror of Infrared Earth Sensor

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Abstract. Tilt angle of scanning mirror is one of the important qualifications of performance measurement on the earth surface for swing scanning mode infrared the earth sensor. In order to settle the problem of measuring the tilt angle of scanning mirror in dynamic, real-time and non-contact, based on laser inspecting technology and CCD probing technology, a method of laser dynamical measurement for tilt angle of scanning mirror of the infrared earth sensor is presented. The measurement system developed in this paper can accomplish the dynamic and static laser non-contact measurement for the parameters of scanning mirror such as tilt angle, swing frequency, etc. In this paper the composition and overall structure of system are introduced. Emphasis on analyzing and discussing the theory of dynamically measuring tilt angle of scanning mirror, the problems of data processing and error correction are settled by established mathematic model of system. The accuracy of measurement system is verified by experiment, the results indicated that measurement range of system for tilt angle is 0~±12°, accuracy of dynamic and static measurement is less than ±0.05°, this method of dynamically measuring tilt angle is suitable.

1. Introduction
The infrared earth sensor is a key component on man-made satellite for measuring attitude, which is used to measure the attitude deviation between the satellite body and the earth. Recurring to optical means, it obtains the attitude information that satellite relatives to the earth. The earth sensor in this mode accomplish the infrared probe scanning the earth by a flat scanning mirror, the information of attitude deviation for satellite is obtained after photoelectric conversion and electric circuit processing system. According to the information, satellite is controlled by controlling system on the earth surface or on satellite. In order to accomplish scanning the earth in measuring process, there is a suit swing scanning mechanism inner of the earth sensor, which is composed mostly of scanning axis, scanning mirror, moving grating, motor rotor, etc. and the scanning mechanism is driven by moment motor, brought along by motor rotor the whole set of axes swing to-and-fro in the range of a certain angle. Scanning mirror is key component of the swing scanning infrared earth sensor, its performance directly influence the accuracy and reliability of the whole satellite, measuring its tilt angle is a technical difficult problem all the while, and which is expected to be settled urgently. Therefore in this paper a method of measuring the tilt angle of scanning mirror in dynamic, real-time non-contact and automatically is presented, which accomplished the dynamic and static measurement for the tilt angle of scanning mirror of the infrared earth sensor.
2. The composition and overall structure of the system
The dynamical measurement system for tilt angle of scanning mirror is composed of semiconductor laser, laser collimating emission optical system, scanning receiving optical system, CCD measuring device, computer real-time control and data processing system, etc. Its overall structure is shown as Figure 1.

![Overall structure schematic of measurement system for tilt angle of scanning mirror.](image)

Lights emitted from the semiconductor laser after passing through laser emission optical system which is composed of collimating, light beam extender and shaping optical system, etc, forms a long strip incident ray on the scanning mirror, the reflected light by scanning mirror forms incident ray on CCD imaging sensitive surface after passing through scanning receiving optical system. When scanning mirror is swinging following the rule of sine, the position of image point on CCD varying along with it. This processed position information by CCD controlling and driving electronics system is transmitted to computer data acquisition system and collected. Then the parameters of position and energy of the information tested can be obtained. The measuring result can be obtained through substituting the parameters of position and energy in established mathematic model and computing. The coordinate curve of tilt angle of scanning mirror about time can be obtained by computer software of data processing.

3. Theoretical analysis of measuring tilt angle of scanning mirror
Because of the limited layout and size of the scanning mirror window of the infrared earth sensor, incident ray can’t pass through gyration center of scanning axis. When scanning mirror is swinging, the position of light spot on scanning mirror surface is moving, namely, the crossing point of incident ray with scanning mirror reflecting surface is translated. But the measurement direction is consistent with reflection ray, inspecting results has nothing to do with the position of this light beam. So a special optical system that is large field of view and linear scanning receiving optical system must be designed in order to meet measuring requirement of outputting tilt angle of scanning mirror.

Measuring principle of system is shown as Figure 2. When the relative positions of semiconductor laser, laser emission optical system, scanning receiving optical system, scanning mirror and linear array CCD are ascertainable, the point $O$ is gyration center of scanning mirror, target surface of linear array CCD locates on focal plane of scanning receiving optical system.

A continuous parallel light ray emitted from semiconductor laser after passing through laser emission optical system incident to scanning mirror. When scanning mirror holds slack, light beam is reflected by scanning mirror, after passing through scanning receiving optical system it focus on center point $C'$ of linear array CCD. When scanning mirror is swinging, because of the alternation of
incident angle, reflecting angle is altering too. According to reflection theorem, suppose the incident ray is invariable and reflecting mirror swings angle $\Phi$, then the reflection ray swings angle $2\Phi$.

![Figure 2. Schematic diagram of measurement system.](image)

Suppose scanning mirror position $2'$ deviates angle $\Phi$ from initialized position $1'$ at random time, and then reflection ray is focused on point $C'$ on target surface of linear array CCD. The distance between $C'$ and $O'$ is $h$. According to geometrical optics principle:

$$h = f'g2\varphi$$  \hspace{1cm} (1)

Negating formula (1) and obtaining:

$$\varphi = \frac{1}{2} \arctan\left(\frac{h}{f'}\right)$$  \hspace{1cm} (2)

In above formula, $f'$ is image focal length of scanning receiving optical system, $\Phi$ is tilt angle of scanning mirror.

According to formula (2), setting $t$ if the sampling interval, measuring a series of value of $h$, then corresponding angle $\Phi$ is obtained.

4. **Method of system error correction**

Because of the laser incident point is not at the swing center of scanning mirror, the position of reflection point will be changed along with the swing angle, so the measuring system is a nonlinear imaging system. As shown in Figure 3, suppose $xoy$ is reference coordinate system and $x'o'y'$ is coordinate system of scanning receiving optical system ($y'$ is superposition with the optical axis of receiving optical system).

![Figure 3. Schematic diagram of system error correction.](image)
When scanning mirror swings in a circle around point $O$, reflection point deviates from original point $O'$ and its position is dynamically varied with angle $\beta$. In coordinate system of scanning receiving optical system, the reflection ray intersects the optical axis at point $A$, the dynamic coordinate of crossing point $A$ is:

$$x = \frac{a \sin \phi \cos \beta}{\cos \left( \frac{\phi - \beta}{2} \right)}$$

$$y = \frac{a \sin \phi \sin \beta}{\cos \left( \frac{\phi - \beta}{2} \right)}$$

(3)

In the above formula, $a$ is the coordinate $y$ in original reflection point reference coordinate system $xoy$, $\beta$ is the angle of original incident ray and reflect ray.

Formula (3) indicates that point $A$ is varied with angle $\beta$, producing off-focus phenomena along optical axis and then bringing system error. When the distance between CCD and optical system main surface is $l'$ and object focus length of optical system is $f$, it can be denoted by the following formula:

$$\Delta h = \left[ 1 + \frac{f}{f + k(\phi)} \right] \tan(2\phi)l'$$

(4)

In the formula, $k(\phi) = y_1 / \tan (2\phi) - x_1$, while measuring tilt angle $h'$ is measured firstly by CCD, and then it is added to formula (4) to get $h$, finally $\phi$ can be calculated combined with formula (2). In the process, $\phi$ is positive and $h$ is negative along clockwise, and $\phi$ is negative and $h$ is positive along anticlockwise.

5. Experimental results

For realizing the measurement of the precision of the tilt angle, calibration measurement is composed of reflecting mirror and optics rotating stage. Reflecting surface of reflecting mirror which is located on optics rotating stage is made to pass through the center of gyration, a given angle by optics rotating stage is regarded as standard value, which is measured by swing measurement system, through comparing the rotate angle of optics rotating stage with the measured value of system, errors of static measurement are obtained. Results are shown as chart 1.

| Angle of positive direction(°) | Angle of negative direction(°) |
|-------------------------------|-------------------------------|
| Rotate angle | Measured value | Error | Rotate angle | Measured value | Error |
| 0.00 | 0.01 | 0.01 | 0.00 | 0.01 | 0.01 |
| 1.00 | 1.03 | 0.03 | -1.00 | -1.02 | -0.02 |
| 3.00 | 3.01 | 0.01 | -3.00 | -2.98 | 0.02 |
| 5.00 | 4.99 | -0.01 | -5.00 | -4.99 | 0.01 |
| 6.50 | 6.50 | 0.00 | -6.50 | -6.46 | 0.04 |
| 10.00 | 9.96 | -0.04 | -10.00 | -10.03 | -0.03 |
| 12.00 | 12.01 | 0.01 | -12.00 | -12.02 | -0.02 |

The measurement curves are shown as graph 4 by measuring the working scanning mirror in real time.

Experimental results and measurement curves indicate that measurement range of system for dynamically measuring tilt angle of scanning mirror is $-12°$ to $12°$, the accuracy is less than $0.04°$. In actual measurement system, it is not only including error of static measurement system, but also install error of optics system, size error of the linear CCD image element and error of electronics processing.
These errors have little influence on the precision of the measurement system by the act of revising, subdividing and electronics optimize processing, and the paper doesn’t discuss these errors in detail.

6. Conclusion

Tilt angle of scanning mirror utilizing photoelectric measurement method put forward in the paper realizes non-contact measurement tilt angle of scanning mirror for the infrared earth sensor. The problems of error correction are settled by constructing mathematic model of system, the dynamic and static laser non-contact measurement for the parameters of scanning mirror is accomplished, that the parameters are positive and negative extremums, difference of peak values, angle of zero position and swing frequency, etc. The accuracy of measurement system is verified by experiment, the results indicated that measurement range of system for tilt angle is $12^\circ$. The research on the photoelectricity measurement for tilt angle of scanning mirror provides essential parameters for the application of the infrared earth sensor, and it also provides the reliable data for the design and manufacture of mechanical system.

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