Position and Attitude Measurement System Design of Boom-type Roadheader

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ABSTRACT: In deep coal seam, high rock-burst and frequent geological disasters lead to high danger coefficient, so research of unmanned mining technology is extremely important. Autonomous position and attitude measurement technology of boom-type roadheader is a core part of unmanned mining technology, which has great research significance. In the boom-type roadheader position and attitude measurement system of this paper, the laser transmitter is equipped on boom-type roadheader to transmit fan-shaped laser beam, and the laser receiver is fixedly set in the rear of the laser transmitter. Based on principle of angle measurement by the fan-shaped laser beam, the position and attitude parameters of boom-type roadheader is measured and calculated. This system is able to achieve autonomous and high-precision measurement of the position and attitude. In this paper, laser-based positioning technology is improved, and the fundamental principle of position and attitude measurement is established. Based on that, the position and attitude measurement system is designed, and the hardware architecture of the fan-shaped laser beam transmitter and receiver is designed and selected. Boom-type roadheader position and attitude measurement system in this paper changes the traditional mode of roadway excavation and lays foundation for unmanned mining in deep dangerous coal seam.

KEYWORDS: Unmanned mining in deep dangerous coal seam; Boom-type roadheader position and attitude measurement principle; Fan-shaped laser beam transmitter; Fan-shaped laser beam receiver

1 INTRODUCTION

Unmanned heading equipment is aimed to achieve automated operation in downhole dangerous area and complex terrain. The research of the unmanned roadheader is aimed to achieve intelligent operation in the unmanned or shojinka situation, so the precise positioning and adjustment must be considered to make the equipment operating according to the given route. In this condition, the roadheader is highly intelligent. In the shojinka situation, the measurement work is precisely achieved, and the manual estimation and the error of manual estimation is avoided.

There are two key concepts in the design of Boom-type roadheader position and attitude measurement system, positioning and attitude measurement. Positioning is to acquire the position information of the roadheader in the coal roadway through the method of measuring a fixed point on the roadheader. Attitude measurement is to acquire the attitude information of the roadheader in the space. There are two specific methods to achieve attitude measurement, the first one is to measure the position data of three fixed and non-collinear points on the roadheader and do some further calculation, the second one is to measure the inclination data of the roadheader’s transverse and longitudinal shaft by inclinometer, connect them with the position data of two fixed points on the roadheader and do some further calculation. (Dong 2005) In conclusion, the precision of attitude measurement is determined by the precision of positioning.

At present, the research of positioning technology is quite hot in the world, and the achievement in this aspect is quite prominent. The existing positioning technology is divided into two categories, wide area positioning technology and local area positioning technology. Wide area positioning technology mainly includes wireless positioning technology, inertial navigation positioning technology and laser radar positioning technology, etc. Local area
positioning technology is divided into the following categories according to different measurement theory, machine vision positioning technology, acoustic positioning technology, laser positioning technology and wireless positioning technology, etc. Among the wireless positioning technology, there are following categories according to different frequency of measurement signal, bluetooth positioning technology, ZigBee network positioning technology, Wi-Fi positioning technology, Css positioning technology and ultra wide band positioning technology, etc. (Yang 2004 & Wang 2011)

The principle of all the above positioning technologies is angle measurement, distance measurement or combination of both. According to the special environment and actual conditions of colliery fully mechanized excavation face, most of the existing positioning technologies are inapplicable. The colliery is in the tunnels hundreds meters underground, so the wireless signal is not able to reach there, and the laneway where the roadheader lays is relatively narrow. Above conditions lead to limitation in the selection of position and attitude measurement method of Boom-type roadheader. In conclusion, laser positioning technology is the most suitable positioning technology in the downhole. (Li 2013)

2 ROADHEADER POSITION AND ATTITUDE MEASUREMENT PRINCIPLE

The existing laser positioning system can be described as laser beam positioning system except laser scanner positioning system. According to the length and angle information relative to the system transmitting terminal of a laser beam from the laser transmitter, the relative position information between the points under test and the system transmitting terminal and the coordinate information of the points under test is able to be acquired. The improved positioning system is a fan-shaped laser beam positioning system, which use the special laser transmitter to lase a beam of fan-shaped laser rotating about a fixed shaft and acquire the space coordinates of the points under test through the three surface intersection principle.

As shown in figure 1, transmitting point A is the origin of coordinates, line AB is the Y-axis of coordinates, rotating shaft of the system transmitter is the Z-axis of coordinates, fan-shaped laser beam 1 rotates about the Z-axis, fan-shaped laser beam 2 rotates about the dash line shaft parallel with the Z-axis, and fan-shaped laser beam 3 rotates about the Y-axis. The space coordinates in this coordinates system of the point under test is able to be calculated through the three plane equation of the three fan-shaped laser beam. The formula is as follows:

\[
\begin{align*}
\tan \alpha \cdot x + y &= 0 \\
\cos \beta \cdot (x - AB \sin \beta \cos \beta) + \sin \beta \cdot (y - AB \sin^2 \beta) &= 0 \\
\tan \theta \cdot x + z &= 0
\end{align*}
\] (1)

Solving the system of ternary linear equations will get the space coordinates expression of the point under test in this coordinates system. The result is as follows:

\[
\begin{align*}
x &= \frac{AB \cdot \sin \beta}{\cos \beta - \tan \alpha \cdot \sin \beta} \\
y &= \frac{AB \cdot \sin \beta \cdot \tan \alpha}{\tan \alpha \cdot \sin \beta - \cos \beta} \\
z &= \frac{AB \cdot \sin \beta \cdot \tan \theta}{\tan \alpha \cdot \sin \beta - \cos \beta}
\end{align*}
\] (2)

Compared to the existing laser positioning system, the fan-shaped laser beam will not be sheltered by obstacles during measurement work, so this positioning system is more suitable to complex environment like the colliery fully mechanized excavation face.

The fan-shaped laser beam should have a certain transmitting angle and be detected and received by the laser receiver within a certain distance. When the laser beam reach to the laser receiver, it should reach a certain numerical value of radiation intensity to trigger the photosensitive element of the receive device and achieve the photoelectric signal transformation when it reach to the laser receiver. In a certain power, the transmitting angle of the
fan-shaped laser beam should be as small as possible to make the most of the light source energy. But too small transmitting angle will make the length of the fan-shaped laser beam reticle too short, and will not satisfy the design requirement.

3 DESIGN OF THE FAN-SHAPED LASER BEAM TRANSMITTER

The laser transmitter need to transmit fan-shaped laser beam while it is rotating, whose key component is the upper rotating head, as in figure 2. The rotating head transmits fan-shaped laser beam, and the measurement system finishes the measurement work through the fan-shaped laser beam. (Yang 2008, Yan 2009 & Liu 2015)

In the overall structure of the laser transmitter, the rotating part of the base station is driven by the electromotor, as in figure 3. The power supply is a rotary power supply module, which consists of two parts. One part is installed on the fixed frame and connected with an external power supply, while the other part is rotating with the rotating part of the base station and the rotating part supplies power to the laser transmitter on the rotating head. The laser transmitter is directly installed on the rotating head, and a cylindrical lens is installed at the laser transmitting place to get the fan-shaped laser beam paralleled with the rotation axis. A high-precision rotation angle sensor is installed on the other end of the electromotor rotation axis, which is able to measure the angle of the rotating head whose fan-shaped laser beam rotates from one laser receiver to another.

3.1 Selecting of the motor

Since the motor driving means is easier to achieve the functions of seal and speed control, motor driving means is selected to this system. According to the size and rotation speed of the fan-shaped laser beam transmitter used on the boom-type roadheader, brushless DC motor is applied as the motivation to drive the laser transmitter in this system.

There are three kinds of DC motor speed control methods: power supply voltage regulation of the armature, attenuation of the exciting flux and armature circuit resistance variation. Among the three methods, resistance variation is able to only achieve step speed regulation, attenuation of flux is able to only achieve stepless speed control on a small scale, while voltage regulation is able to achieve stepless speed control on a wider scale, for which it is the most widely used speed control method. (Chen 1993)

Among the methods of power supply voltage regulation of the armature, PID motor speed control system and are the most widely applicable methods in engineering.

3.1.1 PID motor speed control system

PID algorithm is attempting to regulate the controlled quantity through responding the differential signal in a closed adjustable ring to get desired system response. Digital PID can be descript in (3):

$$P_{out}(t) = K_p[e(t) + K_i \sum e(t) + K_d[e(t) - e(t-1)]]$$  (3)

Fundamental deviation $e(t)$ is the differential value between the current measured value and the setting desired value; three basic parameter $K_p$, $K_i$, $K_d$ are radical constants of the controller, which are respectively referred to as proportionality constant, integration constant and derivative constant. In different systems, the value of three parameters $K_p$, $K_i$, $K_d$ can be adjusted to make the output value and input value remained constant. The system chart of PID algorithm is shown in figure 4.

3.1.2 Phase-locked loop servomotor speed control system

Phase-locked loop is a kind of control system which is able to achieve automatic lock of the phase. According to requirement of input signal, phase-locked loop circuit is divided into constant input loop circuit and servo input loop circuit. The former is applied in systems aiming at frequency stabilization, frequency synthesis and so on, and the latter is applied in systems aiming at tracking, demodulation and so on.
Phase-locked loop is built-up by three basic portions, phase detector (PD), loop filter (LF) and voltage controlled oscillator (VCO), as in figure 5. Phase detector is a kind of phase comparison device, which can compare the phase of input signal $f_i$ and voltage controlled oscillator output signal $f_o$ and generate error voltage $V_d$ corresponding to the phase difference between the two signals. The function of loop filter is to filter the high frequency component and noise of the error voltage $V_d$ to satisfy the required performance of the loop and improve the stability of system. The voltage controlled oscillator is controlled by $V_d$ to make its frequency approximate the frequency of input signal until the frequency difference is eliminated and the frequency is locked.

Phase-locked loop is a kind of phase error control system, which can generate error control voltage to adjust the frequency of voltage controlled oscillator through comparison of phase difference between the input signal and the output signal of voltage controlled oscillator, until the frequency of voltage controlled oscillator is identical with the frequency of input signal. When the loop start to work, if the inherent frequency difference of input signal is already existed, the phase difference must be changing, and the error voltage from the phase detector will keep changing within a certain range. Under the control of the error voltage, the frequency of the voltage controlled oscillator will also keep changing. When the frequency of the voltage controlled oscillator becomes identical with the frequency of input signal, it will keep stability in this frequency. In the stable status, the frequency difference of between the input signal and the output signal of voltage controlled oscillator is zero and will not change with the time, the error voltage keeps stable and the loop goes into locked status. (Pang et al. 2003)

If the voltage controlled oscillator is replaced by an operational amplifier, a motor and an encoder, phase-locked loop servomotor speed control system is built up. A fundamental phase-locked loop servomotor speed control system consists of phase frequency detector, loop-filter, power amplifier, electromotor and incremental opto-electric encoder acting as a sensitive element, as in figure 6. The frequency and phase of the given reference pulse signal according to the requirement of motor speed and the pulse signal from the feedback, is compared in the phase frequency detector to generate voltage signal proportional to the frequency and phase difference. The voltage signal is low pass filtered and amplified to control the motor speed. Once the system is locked, the motor speed can track the frequency of the reference signal, and control precision of motor speed can achieve the precision of the reference frequency. Once the load is changed, the motor speed is changing, and the pulse frequency from the photoelectric sensor is changing correspondingly. It is able to generate frequency difference relative to the frequency of the given signal, and the output signal of the phase detector is changed. The frequency of the feedback signal raises or reduces the motor speed through low pass filter and amplifier circuit, until it is identical with the frequency of the given signal again, and motor reaches stability again. When the system reaches stability, the frequency of the feedback signal is locked to the frequency of the given signal. That is, the frequency difference is zero. (Lin 1983)

Phase detector is the key component of the phase-locked precision, whose substance is a pulse phase comparator, or a special trigger on back edge. The phase detector has two operation conditions, locked mode and frequency difference mode, which are respectively corresponding to the phase and frequency demodulation function of the phase detector. The principle of the two operation condition is shown in figure 7 and 8. As the diagram describing, when the phase detector is working at the frequency demodulation condition, with the increasing of frequency difference $\Delta f = f_i - f_o$, the output average voltage $U_0$ is increasing, the average voltage on the motor is increasing, the motor speed is increasing and the frequency difference is decreasing, vice versa. Phase-locked loop servomotor speed control system regulates the motor speed through this kind of mechanism. (Di et al. 2002)
3.1.3 Comparison of two kinds of speed regulation methods

The precision of general PID motor speed control system is 1%, whose maximum can only reach 0.1% in spite of many optimization methods and the best devices. According to the relative information, the practical application precision of phase-locked loop servomotor speed control system is able to reach 0.002% even higher. (Sun et al. 2000) The persistent error of the rotating head turning 180° is 0.002%, which is the maximum rotation noise caused by the phase-locked loop servomotor speed control system, and the system measurement error is 13° caused by the maximum rotation noise. That is, the precision of phase-locked loop servomotor speed control system is much higher than PID motor speed control system.

In PID speed control system, speed measurement is to get the speed value through calculation of pulse count within a length of sampling time $T$. Two problems are present: the first one is that speed measurement will generate sampling error between the two pulse signal, and the second is the long period of speed control, because when the rotation rate has deviation, speed measurement should be carried out after sampling time $T$ and compared with the setting rotation rate, then the system calls PID to regulate the speed, and the speed regulation will be achieved through above process repeatedly. These two problems cannot be solved completely. To reduce the sampling error impact on speed measurement, the sampling time $T$ should be increased, which will make the speed control period longer. These two problems are paradoxical and cannot be solved simultaneously, and the rotation noise caused by it has serious impact on the precision of the system, while the phase-locked loop servomotor speed control system does not have these kinds of problems. And in phase-locked loop servomotor speed control system, the motor speed will not be impacted by the temperature and the wear of motor.

In conclusion, the phase-locked loop servomotor speed control system is applied in the laser transmitter system.

3.2 Selection of laser head

In consideration of usage convenience in coal mine tunnel operation, the light source applied in boom-type roadway position and attitude measurement system should be visible light. In this system, the red laser is selected as the light source. According to the cooperatively used laser detector, whose detection susceptibility of photosensitive element will increase with the increase of wavelength of light, 650 nm red laser as the semiconductor laser source is appropriate. The performance parameter of the selected semiconductor laser element is shown in table 1.

<table>
<thead>
<tr>
<th>Performance Index</th>
<th>Actual Numerical Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Output power</td>
<td>100 MW</td>
</tr>
<tr>
<td>Working wavelength</td>
<td>650 nm</td>
</tr>
<tr>
<td>Working voltage</td>
<td>3.5-6V (DC)</td>
</tr>
<tr>
<td>Outer diameter</td>
<td>Φ20</td>
</tr>
<tr>
<td>Length</td>
<td>85 mm</td>
</tr>
<tr>
<td>Maximum width</td>
<td>30mm (70-80mm)</td>
</tr>
<tr>
<td>Operating temperature</td>
<td>-10°C-50°C</td>
</tr>
<tr>
<td>Mean time to failure</td>
<td>6000h (30°C)</td>
</tr>
</tbody>
</table>

A set of lens module has to be installed in front of the original laser beam of the semiconductor laser transmitter to convert the original laser beam to laser sector demanded in the measurement system.

To achieve this function, there are generally two kinds of optical element available. The first one is the dedicated optical slit grating, which is able to convert a part of line laser beam to fan-shaped laser beam, and the second is Powell lenses, which is able to convert the whole line laser beam to fan-shaped laser beam with a certain angle through its bulge. Because the cost of the former is higher and the energy loss of its fan-shaped laser beam is relatively serious, the latter is applied in this system.

In the engineering model of this device, a piece of thicken Powell lens is installed in front of the light path of original laser. The thickness of the Powell lens is 18mm, because relatively great thickness is able to satisfy the demand of reliability and protective properties in the coal mine tunnel. In this system, the transmitting angle of the fan-shaped laser beam is 1.5°, so the altitude of the lens bulge is designed to reduce 1mm. The lens is made from K9 optical glass through manual fine grinding. The lens and its light path are shown in figure 9.
4 DESIGN OF THE FAN-SHAPED LASER BEAM RECEIVER

The fan-shaped laser beam receiver is able to perceive the changing of laser signal through the sensitive element, and process the signal to get the measurement results. In the measurement system, the measurement time is very short, so the high demand to response time of the optical detection sensors is necessary. In actual work, the light source is distant with the sensors and coal dust environment will attenuate the laser signal, so the high susceptibility to small-signal is necessary. According to above two demands, avalanche photon diode (APD) is selected as the sensitive element.

The construction and installation precision of the receiver is also crucial to the measurement results, which directly impact on the precision of system. The sensitive element is installed on the surface of the receiver plane, as in figure 10. When the measuring point is on the surface of objects, this receiver is able to make the optical power of received laser reach to maximum and improve the sensitivity of sensors.

Photodiode receives predetermined frequency optical signal, and converts it to electrical signal to achieve the predetermined control mission. The photodiode has two kinds of receive mode, point-blank mode and reflection mode. The point-blank mode means, luminotron and receiving tube are relatively installed on both ends of transmitting terminal and the controlled object, and keep being at a fixed distant away from each other. The reflection mode means, only when the infrared light from luminotron meets reflector, the receiving tube starts to work through receiving the reflected infrared light. According to the application of fan-shaped laser beam, the point-blank receive mode is applied in this system.

Since the signal laser beam is the red laser beam in this system, the sensitivity of laser detecting element have to be high as possible. Avalanche photon diode has small dimension, suitable materials, high sensitivity and rapid response speed. The susceptibility of this photosensitive element has close relationships with the incident angle of the light source. When the incident light source is perpendicular to the photosensitive surface of the element, the output signal of detector is most sensitive, and the detecting sensitivity will decrease rapidly with the excursion of the incident light to the two sides.

Above performances of the detecting element, contributes a lot to the stability of measurement output signal of this device.

5 CONCLUSIONS

In this paper, the boom-type roadheader position and attitude measurement system is designed, including establishment of the measurement principle and design and selection of the hardware architecture, primarily including the following two aspects:

5.1 Principle part
Laser positioning technology is improved, the mathematical models of position and attitude is established based on the principle of angle measurement by the fan-shaped laser beam.

5.2 Hardware architecture part
In the transmitting terminal, design of the fan-shaped laser beam transmitter and selection of motor and laser head have been achieved, and the optical lens of the laser head has been redesigned and improved. In the receiving terminal, design of the fan-shaped laser beam receiver has been achieved to satisfy the function of this system and the demand of coal mine tunnel.

REFERENCES
