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Coal Mine Disaster Rescue Life Sign Monitoring Technology Based on FBG and Acceleration Sensor

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Abstract

The emergency rescue for coal mine disaster is very important to mine security. The environments of coal mine is complicated and dangerous. In order to ensure the self-security of rescuer, minimizing the accident losses, the emergency rescue life sign monitoring sensor based on Fiber Bragg Grating (FBG) and three-axis acceleration sensor are studied in this paper. Firstly, the structure of the emergency rescue system for coal mine disaster is built. Then the life sign monitoring sensor of emergency rescue system for coal mine disaster is studied in detail, includes the detection model of body temperature, the heart rate detection technology for rescue staff, and the detection method of rescue staff posture. Finally, the experiment is made to test the effect of the sensor. The results show that the sensor sensitivity to rescue staff life sign is higher, and it can satisfies the needs of the emergency rescue for coal mine disaster.

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Keywords: emergency rescue; life sign monitoring; Fiber Bragg Grating (FBG)

1. Introduction

Coal is the primary energy and important raw material in China. Coal mine safety has always been paid close attention to. In recent years, with the increasing of coal production, the quantity of coal mine accidents and the number of dead miner in production decreased overall [1]. But compared with the developed countries, the total number of dead miner in accidents is considerable. The safety production status of coal mine is still severe in China.

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The emergency rescue for coal mine disaster is very important to mine security. After the accident, the rescue is an important measure to reduce accident casualties and loss. For a long time past, the coal mine disaster rescue work plays an important role in coal mine disaster relief in China.

The coal mine environments are complicated and dangerous. The body status of the rescue workers needs to be known to ensure the self security of rescuers. At present, the development of the emergency rescue technology is relatively slow in China. The positive pressure oxygen respirator and compressed oxygen self-rescuer used by rescue worker have reached a relatively high level. But the emergency rescue communication command system technology falls behind. The life sign parameters of rescue workers can’t be obtained. The disaster rescue information isn’t real-timely and accurately sent to the underground rescue base, ground rescue headquarters and every rescue command center. The land command staff can’t know the body status of the rescue workers and take measures to ensure the security of rescuers.

Based on the above mentioned, the life sign monitoring sensor technology of emergency rescue for coal mine disaster is studied in this paper. The study plays a significant role in ensuring the self-security of rescuer, minimizing the accident losses, maximizing miners rescue, enhancing the capacity of mine rescue decision, building the fast and efficient nation response system and protecting miners lives to national security.

2. The Structure of Emergency Rescue System for Coal Mine Disaster

The emergency rescue system for coal mine disaster is as shown in figure 1. It is made of emergency rescue life sign sensor, portable data access instrument, repeater station and ground command system. The sensor and portable data access instrument send or receive data by wireless. They’ll support IEEE802.15.4 communication protocol. The communication distance is over 10 meters. The data access instrument and repeater station transmit data by wireless, and the communication distance is over 500 meters. The ground command system mainly includes mobile command platform, dual-system computer and ground repeater station, which can receive in real-time and automatically record the information sampled by data access instrument.

Figure 1. the structure of emergency rescue system
3. The Life Sign Sensor of Emergency Rescue System for Coal Mine Disaster

The rescuers are vital forces for the rescue and treatment of coal mine accidents. The personal safety of rescuers must be ensured. In order to avoid the unexpected incidents while searching, rescuing or handling accidents, the important life sign parameters of rescue workers, such as body temperature, heart rate, posture etc, need to be monitored. The monitoring data is sent to ground monitoring host computer, and the ground command staff can know the physical status at any moment. When the life sign parameters overrun, the alarm displays.

The structure of life sign monitoring module is as shown in Figure 2. It is made of sensor, signal conditioning circuit, data record, microprocessor, memory, power and wireless node. The sensor includes body temperature, heart rate and posture etc sensor units. The data collecting and processing module is responsible for the body temperature, heart rate and posture information collection and primary processing of rescue worker. The microprocessor samples, controls and processes the output wireless signal after pre-processing. The wireless node transmits and receives the data processed by the microprocessor.

![Figure 2 The structure of life sign monitoring module](image)

3.1. The detection model of body temperature

There’re many kinds of temperature sensors, which include contact and non-contact sensors. The thermo-resistive, thermocouple and FBG etc sensors belong to contact sensors. The infrared and ultrasonic sensors belong to non-contact sensors. The optical grating is a new optical passive device which is widely applied to optical sense field in recent years. The optical grating possesses the characteristics of anti-electromagnetic interference, good stability, simple production, small volume, light weight, easy to integrate with optical fiber and can constitute the network advantages etc. The coal mine environment is special. According to the sensor characteristics and the rescue staff body temperature monitoring characteristics, the FBG sensor is used to detect the body temperature of rescue staff.

The rescuer body temperature sensor model is as follows. According to Maxwell’s equations and coupled-mode theory for optical fiber, the basic formula of FBG reflected wavelength is [2]:

\[ \lambda = 2n\Lambda = f(T, \varepsilon) \]  \hspace{1cm} (1)

where \( \lambda \) is the FBG wavelength, \( n \) is the effective index of optical, \( \Lambda \) is the optical grating period, \( T \) is optical grating temperature, \( \varepsilon \) is axial stress.

According to formula (1), there is:

\[ \frac{\partial \lambda}{\partial T} = 2n\frac{\partial n}{\partial T} + 2\varepsilon\frac{\partial \Lambda}{\partial T} \]  \hspace{1cm} (2)

According to formula (1) and (2), there is:

\[ \frac{\partial \lambda}{\lambda} = \frac{1}{n} \frac{\partial n}{\partial T} \frac{\partial \lambda}{\lambda} + \frac{1}{\Lambda} \frac{\partial \Lambda}{\partial T} \]  \hspace{1cm} (3)

Let

\[ \alpha = \frac{1}{n} \frac{\partial n}{\partial T} \frac{1}{\Lambda} \frac{\partial \Lambda}{\partial T} \]  \hspace{1cm} (4)

there is [3],

\[ \Delta \lambda = \alpha \Delta T \]  \hspace{1cm} (5)
Formula (5) is the maths equation of body temperature sensor. Where $\alpha$ is the sensitivity coefficient of sensor. From (5), the temperature change can be got by the wavelength change.

The physical model of temperature sensor is shown in figure 3.

![Physical model of temperature sensor](image)

Figure 3 The physical model of temperature sensor

The FBG central wavelength of physical sensor is 1555nm, and the relations of wavelength and temperature are shown in table 1. From the table 1, we can get that the sensitive coefficient of the sensor is 0.03nm/°C.

| Wavelength(nm) | Temperature(°C) |
|---------------|-----------------|
| 1555.17       | 25              |
| 1555.22       | 27              |
| 1555.27       | 29              |
| 1555.33       | 31              |
| 1555.39       | 33              |
| 1555.45       | 35              |
| 1555.51       | 37              |
| 1555.57       | 39              |
| 1555.63       | 41              |
| 1555.70       | 43              |
| 1555.75       | 45              |

3.2. The detection of heart rate

The traditional testing method of heart rate is to use pulse sensor to detect finger and test the body pulse indirectly. This kind of sensor is good for motionless men. But it isn’t adapted to the motion rescue staff of coal mine. According to the rescue staff heart rate monitoring characteristics and the sensor characteristics, the FBG sensor is also used to detect the heart rate of rescue staff. At the conditions of constant temperature or ignoring the influence of constant temperature, according to hook’s law, material mechanic and formula (1), there is\[3]\,

$$\Delta \lambda_b = \beta \varepsilon$$  \hspace{1cm} (6)

Where, $\beta$ is the sensitivity coefficient of sensor, and $\beta = \lambda_b (1 - P_e)$. $P_e$ is the effective elasto-optical coefficient. $P_e = 0.5n^2[(1-v) p_{12} - vp_{11}]$, where $p_{11}, p_{12}$ are the elasto-optical constant, $v$ is the Poisson ratio.
In order to improve the heart rate detection accuracy, a new method is adopted. The optical grating possesses the characteristics of compatible with yarn[4]. While detecting the heart rate, the sensor is woven into the fabric strap. The fabric strap is tied to the chest. The sensor contacts with the skin of chest directly. The heart beat can produce stress to the sensor, which brings the change of the Fiber Bragg Grating. That is the change of the center wavelength. Then the heart beat of rescuer can be described by the signal produced from the change of the center wavelength.

The principle of the heart rate sensor is shown in figure 4.

![Light source](Light source) → (Fiber bragg grating) → (Wavelength detector) → (Signal conditioning) → (MCU)

**Figure 4 the principle of the heart rate sensor**

For the typical germanium-doped silica fiber, \( p_{11} = 0.12, p_{12} = 0.27, n = 1.46, \nu = 0.17, p_{e} = 0.2187 \). As the FBG of 1330nm, 1335nm, 1340nm, 1540nm, 1545nm, 1555nm wavelength, we calculate the stress sensitivity coefficient according to formula (6). The results are as shown in table 2.

| Code | FBG Center wavelength (nm) | sensitivity coefficient (nm/\( \sigma \)) |
|------|---------------------------|-----------------------------------------|
| 1    | 1330                      | 1041                                    |
| 2    | 1335                      | 1045                                    |
| 3    | 1340                      | 1049                                    |
| 4    | 1540                      | 1206                                    |
| 5    | 1545                      | 1210                                    |
| 6    | 1555                      | 1218                                    |

From the table 2, we can know that the difference of the stress sensitivity coefficient \( \beta \) is smaller when the center wavelength change isn’t bigger. The FBG sensor is mainly used to test the heart rate in this study, and the relationship between the stress value and center wavelength change needn’t be considered. This is a qualitative measure application of FBG sensor. The FBG needn’t be calibrated to be used in heart rate detection. The FBG center wavelength of heart rate sensor is 1555nm.

### 3.3. The detection of posture

The posture detection is very important to the rescue staffs who work in the special environment. The road of coal mine is uneven. There are many obstacles in coal mine. Thick smoke fog and toxic gas produced when the coal mine accidents happened. Some rescue staff can be stumbled by the obstacles for hazy line of sight. Some rescue staff can fall down due to poisoning. If the posture of rescue is detected, the rescue staff can get the rescue change as other rescue staff or ground command staffs know the status when he falls down. So the monitoring technology study of the automatic posture detection alarm is of great positive significance.
At present, the mainly posture detection is image analysis method. The image analysis method can get good effect in the ground. But in coal mine underground, dust consistency is high and smoke fog is thick when coal mine accidents happened. The visibility is low. The image quality is poor. The image recognition is difficult. Moreover, the image analysis algorithm is complex. The system is enormous and the timeliness is bad. The acceleration analysis method is relatively simple and has good timeliness. The acceleration signal is used to recognize the posture of rescue staff in the study.

As is shown in figure 5, when the rescue staff falls down, the X,Y,Z direction acceleration can produced except the inclination, impact and the change of the life sign parameters. So we can recognize the body posture by the acceleration signal. The fall down direction can’t be foreknown. The three-axis acceleration signal is adopted to estimate the posture of rescuer. We can use the inverse proportion relation between the static output from the three-axis acceleration signal and gravity acceleration to analyze the body posture. The posture can be described by the separation angle $\theta$ between body location and gravity acceleration.

From the figure 5, we can know that the maths relation of the angle $\theta$ and the static output of z-axis acceleration signal $Z_s$ is as shown in formula (7).

\[
\theta = \begin{cases} 
-\pi + \arccos \left( \frac{Z_s}{G_s} \right) & (-\pi < \theta \leq 0) \\
\pi - \arccos \left( \frac{Z_s}{G_s} \right) & (0 < \theta \leq \pi)
\end{cases}
\]

(7)

Where $G_s$ is the gravity acceleration and its unit is g, the unit of $Z_s$ is g too. From formula (7), we can get that:

When the rescuer stands in the coal mine, the gravity acceleration will be concentrated in the $-z$-axis. $Z_s = -G_s = -G$, $\theta = 0$. When the man lies or grovels in the coal mine, the output of z-axis nears to zero, and the output value of x-axis or y-axis nears to 1g. $\theta = -\pi/2$ or $\theta = \pi/2$. When the man is in the headstand state in coal mine, $\theta = \pi$. The other postures are shown in four quadrant of figure 5.

4. Experiments effect

In order to validate effectiveness of the life sign monitoring module, the sensor is tied to the chest of employee from china coal research institute to be tested. The experiments are as follows.
Figure 6 (a) Heart rate curve  
Figure 6 (b) skin temperature curve

![Posture curve graph]

From figure(6), we can know that the staff heart rate is about 80bpm, and the skin temperature curve is about 34°. The posture angle is bigger than -90° and smaller than 0°, which means the man is in retroverted state. The testing results agree with the real results.

Conclusions

According to the environments of coal mine and the problems exit in emergency rescue for coal mine disaster, we propose the emergency rescue life sign monitoring technology based on Fiber Bragg Grating(FBG) and three-axis acceleration sensor. The emergency rescue life sign sensor is studied. The experiments show that the method proposed in this study is feasible.

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