

# Research on Fiber Optic Sensor based on Fuzzy Control Theory

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**Abstract**—Fiber optic sensors can be used to monitor deformation and/or the overall integrity of structure components. In this paper, we propose a fuzzy control theory based control principle for sensors, and design a new kind of fiber optic sensor used for Geological monitoring. In order to validate the efficiency of the designed sensor, we simulate a water inrush model in a coal mine, and observe the whole process of the water inrush with our designed sensors. Experiments show that our designed sensors can monitor the whole process of water inrush efficiently.

**Index Terms**—Sensor, Fiber Optic Sensor, Fuzzy Control, Fuzzy System

## I. INTRODUCTION

In recent years, we have been seeing a rapid in the development and use of fiber optic sensors, and they have made many advances many fields [1]. A fiber optic sensor behaves as a transducer that converts a non-optical external perturbation into an optical one. Well established advantages of fiber optic sensors include high sensitivity, light weight, and immunity to electromagnetic radiation. They can also be deployed in harsh and hostile environments. Due to high sensitivity, fiber optic sensors are employed in the monitoring of several physical parameters such as temperature, magnetic field, strain, pressure, viscosity, chemical content, etc. In recent years there has been significant progress in the field of fiber optic sensors for the detection of various chemical species [2]. The most attractive feature of a fiber optic sensor is that they are able to serve as both the sensing element and the signal transmission medium, allowing the electronic instrumentation part to be located remotely from the measurement site. Implementation of fiber optic sensing techniques inside concrete structures signifies a novel interdisciplinary branch in the field of engineering, and entails the distinct blend of laser-optics, fiber optics, optoelectronics, microelectronics, artificial intelligence, composite material science and also structural engineering [3]. But by comparing the overall characteristics and suitability, fiber optic sensors have better facilities and advantages over traditional electrical and other types of sensors. Consequently, fiber optic sensors are currently the prime choice for complete sensing processes with in concrete structures.

Fiber optic sensor technology has gained worldwide recognition due to its specific characteristics. In

engineering, it is mainly used to monitor deformation and/or the overall integrity of structure components with high level of risks or with high safety requirements. Especially in steel-reinforced concrete structures, such fiber optic sensors that have the potential to provide early online information about danger of corrosion are demanded. Fiber optic sensor based monitoring methods are highly welcome for non-destructive assessment of all types of geotechnical and engineering structures because that:

- they cannot be destroyed by lightning strokes;
- they can survive in chemically aggressive environments;
- they can be integrated into very tight areas of structural components, like anchor rods, ropes, composite components, layered concrete elements;
- they enable to deliver sensor chains using one single fiber.

The use of fiber optic sensor systems can be divided, in general, into two main steps:

a) Installed or integrated sensors are activated during testing the structure integrity to collect data about the performance of structure components. Such measurements are mostly carried out periodically, and the sensor state can then be considered as “zero-point” state.

b) In contrast to this procedure, sensors that have to deliver data from the measuring object with reference to the previous measurement must work reliably and stably over years. They must not loose the reference value from the beginning of the signal recording. There are high demands both for operational safety of the sensor system and for reliability of all components (long-term stability of sensor characteristics and related components, accuracy, repeatability of recorded data, consideration of temperature influence, and so no). If zero-point drifts occur, they must be separated from the measurement information. This task might be challenging because the recalibration of sensing elements is, in general, not possible after installation respectively after the first test loading.

Fiber optic sensor usage on-site requires special expertise and experience especially when long-term measurements have to be done. Measurement systems have to work stably under very different environmental conditions, such as temperature variations, moisture influences, chemical attacks to components of the sensor system, chemical interactions between the sensing

elements or specific sensor materials and the measure and or environment. Packaging and ingress/egress areas for fiber optic sensors must be very robust. However, the most relevant issue for long-term monitoring sensor systems concerns the application of the sensing element and/or sensor fiber itself. Application, gluing, crimping or fixing must resist cycling thermal and mechanical loads. In order to consider all quality-related aspects, the only way is to aim at validated sensor systems and validated application methods. By using this methodology, users get the confirmation that the sensor or the measurement system works as reliably as demanded.

A fuzzy control system is a control system based on fuzzy logic—a mathematical system that analyzes analog input values in terms of logical variables that take on continuous values between 0 and 1, in contrast to classical or digital logic, which operates on discrete values of either 1 or 0 (true or false, respectively) [4]. Fuzzy logic is widely used in machine control. The term itself inspires a certain skepticism and sounding equivalent to "half-baked logic" or "bogus logic" [5], but the "fuzzy" part does not refer to a lack of rigor in the method, rather to the fact that the logic involved can deal with concepts that cannot be expressed as "true" or "false" but rather as "partially true" [6]. Although genetic algorithms and neural networks can perform just as well as fuzzy logic in many cases, fuzzy logic has the advantage that the solution to the problem can be cast in term that human operators can understand, so that their experience can be used in the design of the controller. This makes it easier to mechanize tasks that are already successfully performed by humans.

The rest of the paper is organized as follows. In section 2, we review related work on fiber optic sensor and fuzzy control theory. In section 3, we present the designed fiber optic sensor based on fuzzy control theory. In section 4, a water inrush model of a coal mine is observed using our designed fiber optic sensor. Conclusion and future work is given in section 5.

## II. RELATED WORK

In this section, we review related work about optic fiber sensor and fuzzy control system.

### A. Fiber Optic Sensor

Fiber optic sensors can be classified in a range of ways, and a fuller classification scheme for all optical fiber sensors has been given by Ning and Grattan [7]. This aspect is not expanded upon in this paper but the essentials of that classification are used. This paper classified optical fiber sensors according to whether they have one or more of a range of optical sources and a modulation scheme by which the measure and introduces a change in the optical signal.

#### Interferometric sensors

This has been a major aspect of the study and effective use of interferometric sensors for some years, where in normal sensor operations a measure and induced phase shift, which is proportional to its influence on the optical system, is encoded by the interferometer transfer function into an intensity change at the detector in a non-linear

way, via the familiar cosine interference function. A number of schemes have been applied to the tracking of these phase changes, including the earliest, active homodyne tracking, which has proved useful for stabilization of the interferometer in simple situations. However, devices based on this principle have been less than acceptable for more widespread applications. This is because of the need for an electronically driven element in the sensor system to change the interferometer conditions, which is not well suited to what is otherwise an all-optical device. In many cases, this negates the advantage of having an optical method of measure and determination. Various laser frequency modulation techniques have been reported, including the "phase-generated carrier approach" to create phase shifts of the carrier signal in the unbalanced interferometer. Techniques of this type have been discussed in some detail by several authors, including Kersey [8] and Rao and Jackson [9] and recently, Lu and Pechstedt [10] have analyzed the effects of the phase modulation characteristics on the performance of a two-beam interferometer incorporating active homodyne processing techniques.

#### Multiplexing of fiber optic sensors

The promise of successful multiplexing schemes was one of the early features promoted as a major benefit of fiber optic sensors over conventional devices. Multiplexing of sensors offers the possibility of the use of a common source and detection system, and one of the advantages of optical fiber systems is the fact that for some sensors, multiplexing can be achieved in a relatively straightforward way. There are three major multiplexing arrangements that may be used wavelength division WDM, frequency division FDM, and time division TDM multiplexing, and in addition, spatial division multiplexing [11]. SDM and coherence-domain multiplexing CDM are considered and discussed below [12]. Various combinations of these techniques are possible to extend the numbers of sensors on a single network. They are generally applicable to any of a range of different "point" sensors but have been most closely associated recently with either Bragg grating or interferometric systems where multiplexing schemes are such that a large number of sensors may be used [13]. Multiplexing is very important in optical fiber sensor systems to reduce cost and maximize the impact of the measurement process. The signal processing aspects clearly become more complex but there are significant advantages in creating such systems for a range of sensor applications.

#### Distributed fiber optic sensing

The development of a distributed sensor system relies upon using a known and reproducible method by which the measure and can interact with the light travelling in the fiber. Most distributed optical fiber methods employ non-linear optical effects in the silica material from which the fibers are made. The fundamental reason for this is that these effects exhibit varied and distinctive responses to external measure and, thus providing for the development of a range of a range of applications-

specific sensors [14]. The most popular approach has been to use backscatter methods, employing convenient laser sources and using OTDR [15] as this allows for a useful spatial resolution typically a few meters and has the advantages of high sensitivity and operation from one end of the probe fiber. Their disadvantage is that of a low-level signal due to the low non-linear coefficients of the silica, which constitutes the fiber and thus this gives quite a long system response time in typical systems, resulting from the necessity to integrate the small signals received over many pulses. The forward-scatter techniques [16], usually employing counter-propagating pulse-wave interactions, generally are of lower sensitivity and normally need access to both ends of the fiber to recover the interrogation light pulse, but they often provide sufficiently powerful signals to operate in a "single-shot" mode. This tends to give a response time not greater than that of the "go-and-return" light passage along the fiber.

### B. Fuzzy Control Theory

Nath et al. [17] report a simple, cost-efficient fiber-optic sensor for monitoring pressure fluctuations in ON/OFF state. The working principle of the proposed sensor is based on light intensity modulation of a reflected signal when external pressure fluctuations cause coupling optical signal variation between two multimode optical fibers placed side by side in front of a plane reflecting mirror attached on a pressure-sensitive diaphragm. The proposed sensing technique is found to be suitable for monitoring both periodic and non-periodic forms of pressure variations in ON/OFF state. With their proposed sensor design, pressure variation as small as  $1.5 \times 10^{-5}$  N/cm<sup>2</sup> can be measured with accuracy and repeatability.

Antonio-Lopez et al. [18] proposed and demonstrated a novel liquid level sensor based on multimode interference (MMI) effects. By using a multimode fiber (MMF) without cladding, known as no-core fiber, liquids around the MMF modify the self-imaging properties of the MMI device and the liquid level can be detected. They show that the sensor exhibits a highly linear response with the sensing range and multiplexed operations easily controlled by just modifying the length of the no-core fiber. At the same time, they can measure the refractive index of the liquid based on the maximum peak wavelength shift, and can also use the sensor for continuous and discrete liquid level sensing applications, thus providing a liquid level sensor that is inexpensive with a very simple fabrication process.

Chen et al. [19] proposed and demonstrated a highly sensitive Microbend Fiber Sensor (MFS) for Ballistocardiogram (BCG) recording. The MFS based BCG sensor is built into a cushion. It is a portable, small, light and low cost device. High quality and repeatable BCG signals can be obtained by using this device which allows patients at home to monitor their cardiovascular health. The measured BCG waveforms closely resemble those in the existing literatures. The BCG heart beat detection agrees well with one from photoplethysmography (PPG) signal.

Traffic congestion is one of the worst problems in some cities of many countries. Recently, it is a hot topic to develop an effective real-time control system for traffic signals at intersections. Wang [20] presented a method to design a real-time FPGA-based fuzzy control system for traffic signals at an intersection. The approach is by using fuzzy logic to optimize green time during peak or off-peak hours. The proposed traffic signal control method is a more universal and intelligent approach to the different traffic states and has been implemented using FPGA in the laboratory. This traffic signal control system is implemented on ALTERA chip and simulation results have been proven to be successful, especially its real-time responsive to variable traffic flow.

Khayat et al. [21] described a fiber optic sensor for two-dimension linear displacement measurements. This sensor can have resolution and range in nanometer and millimeter scales, respectively. After validation of the sensor principle in one dimension, the displacement methods in two dimensions are described and the experimental measurements are realized by the use of the sensor and high precision actuators. The best and the worst displacement cases are realized with measured limits of resolution of 27.4 nm and 38.7 nm in the range of 8.67 mm and 13.03 mm, respectively.

## III. FUZZY CONTROL THEORY BASED FIBER OPTIC SENSOR DESIGNING

In this section, we design a fiber optic sensor based on the fuzzy control theory. First, we introduce our design of the design of the sensor, and then present the control principle of the fiber optic sensor.

### A. Sensor Designing

In the field of science and technology, the wide - ranging use of fiber optics and its realistic applications surfaced rapidly and as time progressed, it made a huge advancement by having a positive impact on world- wide communication technologies. This specific technology possess distinguishing and very useful characteristics, such a slow-cost, incredible capacity for carrying accurate information from one place to another, and total invulnerability to many types of significant interference. Fiber optic sensors (FOS) are one of the most reliable and versatile types of sensors that have brought about many noteworthy improvements to a variety of measurement systems and technologies; these improvements are similar to those that fiber optic technology brought to modern telecommunication systems. Practical implementation of fiber optic sensors for synchronized structural health monitoring of concrete structures is one of the most important and ongoing fields of research and the ultimate goal is to obtain the most accurate data in order to monitor the condition properly and to take effective steps. The structure of the proposed fiber optic sensor is in figure 1. First, the light is launched into the fiber. After being sent out of the Modulator, it is photo-detector demodulated. Last, the output of the last step is sent to another Modulator, and the output of this step is the measured signal that we need.

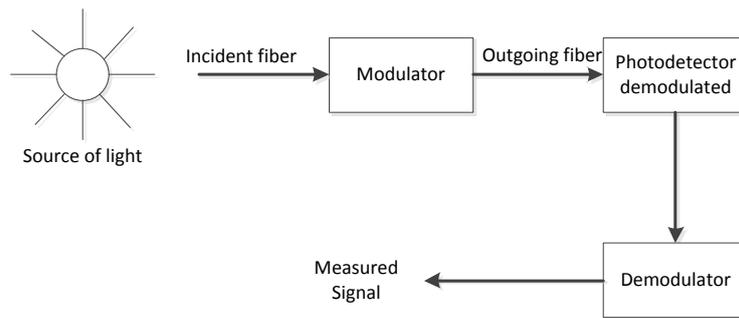


Figure 1. Structure of fiber optic sensor.

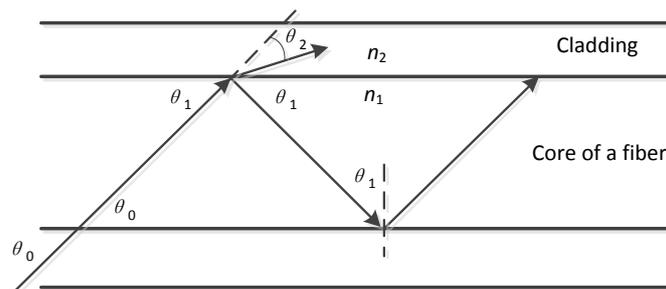


Figure 2. Transmission principle of light in a fiber

Consuming that the light has a small incident angle  $\theta_1$  in figure 2, the light is from optically dense media  $n_1$  to optically sparse media  $n_2$ , and then some of the light will refract to the optically sparse media with the angle of  $\theta_2$ , and others will reflect to the optically dense media with the angle of  $90^\circ - \theta_1$ . Hence, the relation between the incident direction and the refract direction is

$$\frac{\sin \theta_1}{\sin \theta_2} = \frac{n_1}{n_2} \tag{1}$$

where  $\frac{\sin \theta_1}{\sin \theta_2}$  is a constant value. If we improve  $\theta_1$ , then  $\theta_2$  will also be increased. While  $\theta_1$  is improved to  $\theta_c$ , the refract angle  $\theta_2 = 90^\circ$ , that is the refract light refracts the interface direction, and then the incident angle is called the Critical Angle. Hence, we have

$$\sin \theta_c = \frac{n_2}{n_1} \tag{2}$$

When the incident angle is bigger that the critical angle, the light will not penetrate the interface, and they all reflect to the inner part of the optically dense media, and this is called the total reflection. The angle  $90^\circ - \theta_1$  between the light and the interface is smaller than a constant value, the light will not be sent to outside of the fiber, and propagate forward along the road between the

core and the cladding layer interface continuously in reflection.

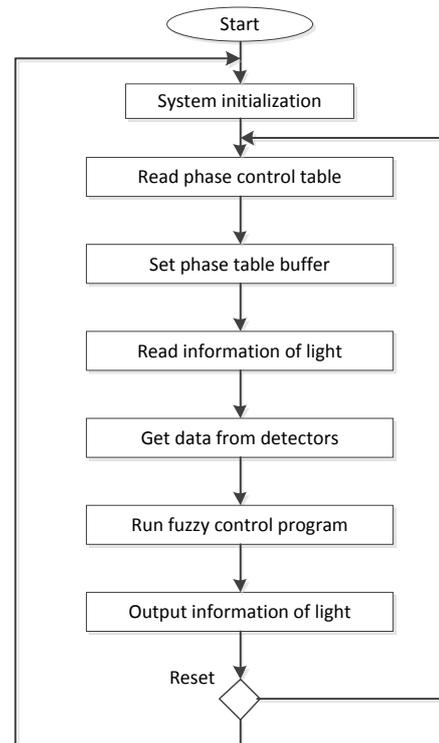


Figure 3. Transmission principle of light in a fiber

Usually, there are two forms of the change of refractive index between the core and the cladding layer, Step-index and Graded-index, and the difference between them is the reason that causes the propagation of light. The goal is to make light lossless from one side pass to the other end. In fact, when the light propagates in the fiber, the energy attenuates. Suppose that the incident power and the outgoing power of the incident end and the outgoing end are  $P_i$  and  $P_o$ , respectively, the attenuation of power of the fiber  $\alpha$  can be computed by the following formula:

$$\alpha = \frac{10}{L} \lg \frac{P_i}{P_o} \quad (3)$$

where  $L$  is the length of the fiber.

**B. Control Principle**

Fuzzy control theory is applied in the design of the fiber optic sensor. An obvious advantage of fuzzy control systems over traditional ones is their ability to use expert knowledge as such, in the form of fuzzy rules. Another advantage of fuzzy control is the small number of parameters of the membership functions needed to be selected. The parameters needed in fuzzy control are easy to comprehend and making the design process is more suitable for human-like reasoning.

Fuzzy control method for fiber optic sensor

Based on the technique of the fuzzy control theory, the light control algorithm can be summarized as follows:

- Step1: Initialize system parameters, such as the phases' minimal time  $t_{min} = 15s$ ,  $g_{max} = 30$ , the maximal cycle  $t_{max} = 130s$  and the maximum of queuing vehicles  $Q_{max} = 20s$ . Suppose  $i$  is the sequence number of traffic signal current phase.
- Step2: When the minimal phase time is end, calculate the extended time  $\Delta t_i$  of the current green time according to the detected traffic data ( $q_i$  and  $q_{i+1}$ ), then run the fuzzy control program and get the output of fuzzy controller.
- Step3: Calculate the phase time of current phase after optimization. If the current phase  $i$  is end, then set  $i$  equal to  $i+1$ , run the next phase.
- Step4: If the cycle time is end, then continue the next cycle and return step1. If the final phase is end, then go to the next cycle.

The control follow the fiber optic sensor is in figure 3.

**IV. EXPERIMENTAL RESULTS**

In this section, we use the designed fiber optic sensor to detect the water inrush of a coal mine.

**A. Experiment Setup**

In order to study the evolution before water inrush, we build a physical model containing large concealed water, and the size of the concealed water is 50cm×30cm×30cm. The ratio of original model to the experimental model is C=100, and thus the size of the model is 1.8m×1.5cm×0.5cm. Materials of the simulation

experiments are similar material, such as paraffin wax, sand, talc, etc., and they are made by a certain percentage. This model has the same attribute with rock, and has a very big adjustment range of permeability coefficient, that is  $1.2 \times 10^{-7} \sim 5.0 \times 10^{-4}$  cm/s. In this experiment, we don't take load into consideration, link the external catheter with inlet pipe of the concealed water, and simulate water press by adjusting the water height of the outlet pipe. The lithology and thickness of the model top down are Overburden 68cm, Aquifer 30cm, Soft rock 9cm, Hard rock 5cm, immediate roof 2cm, Coal seam 10cm and Bedrock 56cm. The concealed water locates in the middle of the aquifer position.

**B. Sensor Placement**

If we begin to mine the coal from the coal seam, then the soft rock and anti-sudden critical layer beneath the concealed water are prone to collapse. Hence, we should focus on monitoring the key location, and in order to accurately capture the corresponding displacement, strain, and osmotic pressure, we determine 10 key points in the model, and its concrete position is in figure 3. In this model, we bury 10 fiber optic sensors, and they are in locations 1 to 10, respectively. The center of each fiber optic sensor is at the monitoring point, and they can monitor the temperature the designed location timely. In our experiment, we first build the experimental model, and then bury the fiber optic sensors. This can make sure that the location of each sensor is accurate. Moreover, as the optical fiber is very thin and brittle, we should take care of these sensors while burying.

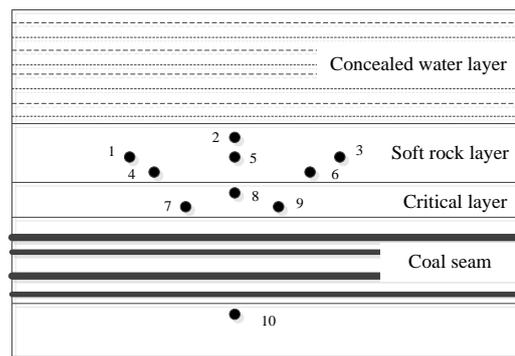


Figure 4. Key points of the sensor layout

**C. Data Collection**

The center wavelength of the fiber grating is the MOI Company production of four-channel fiber grating demodulator sm-125. This demodulator can collect data automatically, and measure parameters, such as stress, temperature, displacement and pressure, etc. Its resolution of wavelength can be up to 0.1pm, and its scanning frequency is 1Hz.

In this model, the ten buried fiber optic sensors construct a local area network by Wavelength Division Multiplexer. By signal transmission, the measured signal is transmitted to the fiber coupler signal transmission fiber, the input end of the fiber coupler connect directly

the grating demodulation instrument, and thus forms a complete fiber optic sensing network.

*D. Experimental Process*

Before digging, we record the initial reading of each sensor, and then fill concealed water through the external catheter to the insidious water, until it is full and all readings of sensors are stable, then we begin to collect data from all sensors. After the first step of digging (about 10 minutes), we wait until all readings of sensors are stable, then we continue the second step, and then the third step, etc. While we continue the 8-th step, the outburst prevention critical layer collapses.

In the experiment, the phenomenon of model collapsing and the water inrush that we observed is that: before the water inrush, the ionospheric phenomenon happens in the critical layer first, and then the seepage amount increases significantly; as the aggravation of the ionospheric phenomenon, the middle position of critical layer cracks from the bottom, the crack scales up rapidly, and then the critical layer cracks entirely. It takes 30 minutes from the critical layer ionospheric to cracking entirely, and about 90 minutes later, the concealed water body collapses at the bottom layer, and then water inrush occurs.

*E. Results Analysis*

From figure 5 we can see that, in the outburst prevention layer, middle of surrounding rock displacement continues to increase, the earliest vertical displacement surges at about 15000 seconds. From figure 6 we know that, in the mining process, the outburst prevention layer internal stress state adjusts constantly, and the small amplitude phenomenon of sudden increase of the stress value appears at about 12800 seconds.

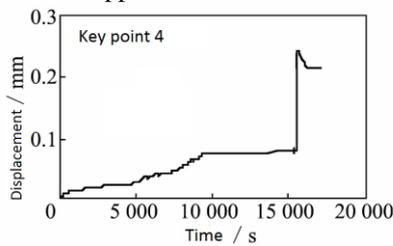


Figure 5. Time-history curves of displacement.

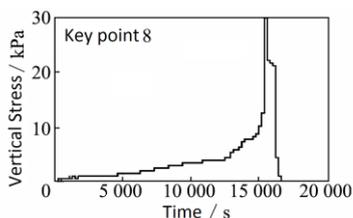


Figure 6. Time-history curves of vertical stress.

Later, stress increases significantly, which means that this location will have a big displacement. This phenomenon indicates that the outburst prevention layer will crack soon. Figure 7 describes the duration curves in the outburst prevention layer near the middle of the osmotic pressure of the surrounding rock. When we dig at about 6000 seconds, the water inrush phenomenon

aggravates, and the osmotic pressure degrades just small amplitude, and we predict that the excavation leads to fissures and continue perforation. Hence, the dump of osmotic pressure is also extremely important precursory information of water inrush. As can be seen from figure 8 that, because of the lower temperature of the test water, as the water inrush gradually, the temperature of key point degrade rapidly, and stabilize about 7000 seconds later.

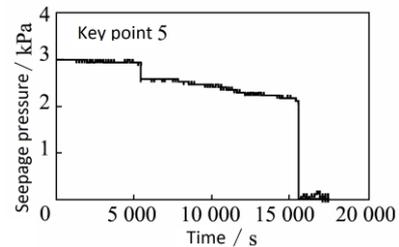


Figure 7. Time-history curves of seepage pressure.

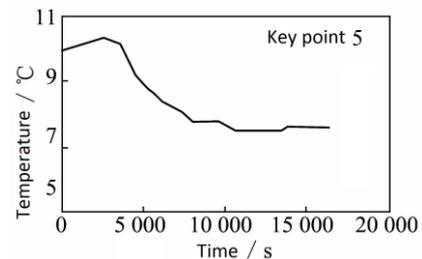


Figure 8. Time-history curves of temperature.

From the above observed results, we have that the sensed water inrush process is almost the same with the practical process, which indicates that our designed sensors are efficient in monitoring the deformation and/or the overall integrity of structure components. Meanwhile, our experimental environment is simulated the same with a real coal mine, and this will make us believe that our designed can also work in real industry environment.

V. CONCLUSION AND FUTURE DIRECTIONS

In the past 20 years, the design of fiber optic sensors has evolved from the use of simple de-cladded fibers to tapered geometries with surface modifications. Fiber optic sensors have been used for many biological applications such as the detection of pathogens, medical diagnosis based on protein or cell concentration, and real-time detection of DNA hybridization. In this paper, we design a fiber optic sensor based on the fuzzy control theory. In order to test the efficiency of the designed fiber optic sensor, we simulate a water inrush model in a coal mine, and observe the whole process with our fiber optic sensor.

In terms of detection principles, it appears that intensity based sensors have been used to a limited extent in the detection of cells. However, for the protein and DNA detection, the use of fluorescence fiber optic sensors has been widespread because amplification is often necessary to detect low levels of biomolecules at UV and visible wavelengths. Perhaps due to the small size of these molecules, intensity or absorption based

sensors are not sensitive enough. More recently, SPR has evolved to become one of the most commonly used methods for protein characterization. SPR was originally used with a chip but there have been a few successful studies combining SPR and optical fibers. The ng/mL sensitivity provided by SPR suits many clinical applications. While fluorescence provides an attractive platform in terms of selectivity, its sensitivity is surpassed by SPR. In addition, fluorescence methods require multiple steps for sensor or sample preparation.

As for applications, one possible area of growth is the use of SPR or intensity-based fiber optic sensors for the detection of protein and DNA. The DNA-based detection is increasingly being used for pathogen detection, and most methods reported to date use fluorescent labeled DNA. Another area of growth is drug screening using fiber optic sensors by making chemical modification on the fiber surface. Because of recent concerns of security, there will likely to be significant development in the detection of bio-threat agents. Detection of pathogens also remains important in maintaining a safe environment and food supply. In addition, clinical applications of fiber optic sensors will continue to flourish along the advancement of medical diagnostics. After surveying the large number of studies on fiber optic sensors, it appears that detection of cells using antibodies as recognition molecules is lacking across all platforms, and this is one important area that is likely to grow in the future.

There are many challenges in the development of fiber optic sensors. One challenge is the high LOD faced by intensity-based fiber optic sensors. Thus far the most popular method to overcome this challenge is to utilize fluorescent labels to amplify the signal associated with the presence of the target. However, the disadvantage of fluorescence is the limited lifetime of fluorescent molecules and the need to prepare a second labeled target or antibody for detection. SPR is an attractive method because it does not require any labeling. As a result, there has been a shift in protein and increasingly DNA detection to using SPR; however, some disadvantages of SPR include its large size and high cost. The development of fiber optic-based SPR should alleviate some of these problems provided that the high sensitivity is retained. One area of fiber optic sensors which has been investigated to a limited extent is the use of longer wavelengths. The use of longer wavelengths has been used with some success in chemical sensing, but has not caught on in bio-sensing because of the challenges associated with water absorption at long wavelengths. If long wavelengths are to be used in fiber optic sensors, it is necessary to functionalize the surface of the fiber optic sensors so that water is excluded, or detection is carried out at a wavelength where absorption of water is minimal.

As fiber optic sensors evolve, new effort will be focused on enhancing the sensitivity and selectivity. It appears that methods based on SPR and fluorescence have reached a plateau in terms of detection limit, and one possible future direction is to combine the two methods so that the SPR signal is enhanced. Improved surface chemical modification and stability of the

recognition molecule can also increase the sensitivity and robustness of fiber optic sensors, especially for intensity-based fiber optic sensors because it is the most sensitive when molecules are bound to its surface. As was shown in this review, there is a solid foundation of work to support the use of fiber optic sensors in a wide variety of applications. Given its promising advantages, it is likely that fiber optic sensors will remain a popular choice among researchers and practitioners for detection of biological agents.

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