Fibre Optic Conveyor Monitoring System

Ben Yang Yang
B.Eng. (Mechanical Engineering)

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The University of Queensland in 2014
School of Mechanical and Mining Engineering
Abstract

Transporting coal by means of conveyor belts is common in Australian underground coal mines. Major conveyor belt–related mining incidents are now relatively infrequent as a result of recent improvements in engineering standards and the use of fire-resistant materials. However, conveyor belts are still a potential cause of personal and structural damage. In addition, any unexpected breakdown of rolling components or failure of belts creates a significant interruption to production, which is a major concern for operators, who are responsible for achieving optimum mining production.

This project aimed to develop a fibre optic–based distributed temperature sensing (DTS) system to monitor the temperature change of malfunction idlers for heavy-duty conveyor belts in underground coal mines. Specifically, the objective of the project was to investigate various installation options for fibre-optic cable along the conveyor belt in order to identify the most effective design. The project was consisted of site trials and laboratory experiments to examine the performance of the DTS system for different cable installation designs and to characterise the behaviour of the DTS system.

The results of the site trials and laboratory experiments proved that the fibre optic–based DTS system is a suitable monitoring system for conveyor belts that can accurately and in real-time identify the faulty idlers that generate heat. The location of the fibre-optic cable with respect to the heated idler plays an important role in the sensitivity and reliability of such a monitoring system. Conduction heat transfer was the only means of heat transfer by which the temperature rise of the faulty idler could be sensed. The fibre-optic cable should be attached to the frame of the idler and as close as possible to the bearing without interfering with the conveyor operation and maintenance. There was a trade-off between the accuracy and response time of the temperature measurements, and the simplicity of the fibre-optic cable installation. The results of the Kestrel North coal mine test proved that the DTS monitoring system is able to provide a real-time temperature profile of the conveyor belt structure and the surrounding area so that the operator can observe the roadway temperature conditions and make critical decisions in serious situations.
Declaration by author

This thesis is composed of my original work, and contains no material previously published or written by another person except where due reference has been made in the text. I have clearly stated the contribution by others to jointly-authored works that I have included in my thesis.

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August 2014
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### Publications included in this thesis


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List of Abbreviations used in the thesis

**ACARP**: Australian Coal Association Research Program

**DTS**: Distributed Temperature Sensing

**DUT**: Device Under Test

**GaG**: Gorniczy Agregat Gasniczy

**LED**: Light Emitting Diode

**MSHA**: US Mine Safety and Health Administration

**OFDR**: Optical Frequency Domain Reflectometry

**OTDR**: Optical Time Domain Reflectometry

**QBH**: Queensland Bulk Handling

**RTD**: Resistance Temperature Detector

**UQ**: the University of Queensland
CHAPTER ONE

Introduction
1 INTRODUCTION

1.1 BACKGROUND

Conveyor belts have been used widely in the mining industry for over 200 years to handle bulk materials ranging from very fine, dusty chemicals to bulk materials, such as raw ore, coal, or overburden, including stones, soil and wood logs (Hetzel and Albright, 1941). In comparison to other transportation methods for bulk solids, such as trains or trucks, conveyor belts are an extremely favourable choice for instances where the road and railway infrastructures do not exist or are under development (Pang, 2010). From centuries of experience, conveyor belts have proven to be a system that has a relatively low cost of equipment, labour, power and maintenance, but high capability and reliability. The length of a conveyor belt system varies from ten metres to tens of kilometres, while the width of the belt varies from 0.2 m to 3.2 m. Today, the conveyor belts with the highest capacity carry up to 40,000 t per hour (CEMA, 2007).

![Heavy-duty conveyor belt in an underground coal mine (Markham, 2010).](image)

A conventional troughed conveyor belt consists of varied components including an endless belt to carry the material; idlers, which are mounted on the frame structure, to support and hold the belt, pulleys to drive the belt, a take-up device to control the belt tension and a driver unit to power and drive the pulley. The configurations of each component vary depending on the design requirements for different situations. The reliability of such a system depends on the reliability of each individual component. The malfunction of one component may lead to significant downtime in production if it causes the shutdown of the system. Engineers spend
considerable time and effort to increase the reliability of each component in order to provide a reliable system. Nevertheless, the reliability of the components is constantly reducing as the operation period goes on. A regular maintenance plan and a suitable malfunctioning components detection method are compulsory during operation.

The mechanical components of conveyor belts create heat or noise when they encounter functional failures. Today, regular inspections of the condition of conveyor belts are carried out by well-trained and experienced technicians. The malfunctioning components are detected with thermal or acoustic handheld devices and subsequently, the necessary maintenance activities, such as component replacement or repair, can be carried out. However, there are several considerable problems involved in the process. Firstly, significant human effort and specialised knowledge are required: the inspectors must be knowledgeable and have extensive experience in conveyor belt maintenance. The long-term labour cost is substantial given that the life of a mine can span decades. Secondly, component failure can lead to major damage to the surrounding infrastructure and risk of injury to personnel. Unavoidably, technician inspection-based monitoring methods expose personnel to hazardous environments.

1.2 Problem Statement and Potential Solution

An advanced intelligent monitoring and operational control system is required in order to overcome the defects in the current system; however, there are two major barriers to such an upgrade. First, collecting up-to-date data from conveyor belt components which are highly distributed over a large area is difficult and complex. Monitoring and gathering physical information of the bearings on the idlers requires thousands of sensors on the conveyor belt structure. Second, the transmission, analysis and interpretation of all the collected data is also challenging, especially in an underground coal mine environment where electrical cables and electronic devices are restrict to intrinsically safe.

A Distributed Temperature Sensing (DTS) system, using the latest optical fibre technology, is an intrinsically safe method that can be utilised in underground mine operations. The system is able to provide continuous measurements and monitor the temperature variation of the rolling components on conveyors to identify any mechanical failures at an early stage. The DTS system is comprised of a DTS unit and a fibre optic cable. The fibre optic cable is not only used to transmit data, but it also senses the temperature. The DTS system provides a continuous temperature distribution profile along the entire length of fibre optic cable with
extremely high accuracy. Typical temperature accuracy is ±1°C, the temperature resolution is 0.01°C and the spatial resolution is 1 m. The measurement distance varies from 10 m to 30 km and is less affected by the potential anomalies within the fibre, such as bends and connections. The advantages of the system include accuracy, low cost, easy installation, robustness, safety, immunity to radio frequency and electromagnetic interference, real-time data collection and secure data transmission.

1.3 AIMS AND OBJECTIVES

This project aims to develop an innovative fibre optic-based DTS system to monitor the temperature change of malfunctioning idlers for heavy-duty conveyor belts in an underground coal mine environment.

In order to achieve this goal, the following listed objectives need to be accomplished:

- Determine the DTS system’s functional characteristics using laboratory experiments. The study covers a series of experiments within the fibre optic cable installation criteria on conveyor belts and also examines the difficulties that could arise in the intended application.

- Utilise and examine the fibre optic cable installation configurations on conveyor belts to identify the optimal configuration in the trade-off between fine measurements and simpler installation.

1.4 SCOPE

This project studies and indicates the functional characteristics of the DTS system that exists in current market. Characteristic validation experiments include the DTS temperature measuring method, the temperature measurement fluctuation with respect to varying measuring time, cable length exposure and the effect of bending. The performance of various cable installation accessories in laboratory experiments are able to indicate the installation criteria on conveyor belts.

In this project, the design and implementation of fibre optic cable will be tested with various installation configurations on heavy-duty conveyor belts in surface site trials. The effect of underground coal mine environment conditions, such as ventilation, vibration, and variation of ambient temperature, will be examined. The study introduces the utilisation of a DTS
system in the monitoring of the condition of underground coal mine conveyor belts, as well as providing a temperature profile along the conveyor belts where the cable covers.

1.5 Significance to Industry

This research project expects to deliver a new generation conveyor belt monitoring system to significantly improve operational safety and reduce the interruption to production of conveyor belts in underground coal mines by delivering the following benefits:

- providing real-time, reliable, robust, intrinsically safe and continuous temperature measurements for heavy-duty conveyor belt components
- detecting the mechanical failure of conveyor belt components at an early stage
- reducing the labour time and cost of conveyor belt monitoring
- preventing catastrophic failures of conveyor belts
- presenting operators with useful information on conveyor belt conditions
- measuring conveyor belt surrounding temperature profiles.

1.6 Thesis Outline

The study starts with a background introduction to both conveyor belt structure and DTS operation principles, followed by the laboratory experiments layout, results and discussions. Site trials design and implementation covers the examination of prototype concept performance and other challenges in an underground coal environment.

Chapter 2: Conveyor Belt Failure and Monitoring provides an overview of the structure of heavy-duty conveyor belts in the underground coal industry. The chapter reviews and determines the potential failure mode of the components that most commonly fail and identifies current gaps and opportunities in the monitoring methods.

Chapter 3: Distributed Temperature Sensing introduces the fundamental study of fibre optic-based sensing technologies and a feasibility view of the fibre optic-based sensing system solving the research question. The principles, advantages and applications of the DTS system are reviewed in this chapter.
Chapter 4: Experimental Set-Up gives an overview of the experiment set-up in both the laboratory and site tests. This chapter introduces details of the equipment and methods used in this project, including the DTS system, fibre optic cables, splicing method, multiple heat simulation methods and other temperature sensors used for cross-validation.

Chapter 5: System Characterisation presents the investigations and results of the functional characteristics of the DTS monitoring system corresponding to different heat transfer methods, sampling time, the bending of the fibre optic cable and cable exposure length. The design of various cable holders are based on the findings of the characterisation tests.

Chapter 6: Site Experiments shows the results of implementing the DTS monitoring system on surface conveyor belts with respect to various possible effect parameters, such as the cable layout, vibration, ventilation and ambient temperature variation. This chapter investigates the performance of different cable holders in response to different installation locations.

Chapter 7: Conveyor Monitoring during Inertisation presents the significance of the DTS monitoring system for an underground conveyor belt. Particularly, the real-time monitoring of the surrounding mine temperature profile helps to provide critical information in extreme scenarios.

Chapter 8: Conclusions and Recommendations concludes the work on fibre optic-based DTS system monitoring of heavy-duty conveyor belts in underground coal mines and points out the direction for future studies.
CHAPTER TWO

Conveyor Belt Failure and Monitoring
2 CONVEYOR BELT FAILURE AND MONITORING

Conveyor belts have been used widely for centuries in the mining industry to handle a range of bulk materials. Conveyor belts consist of multiple components and the reliability of the components reduces as the operation period goes on. A regular maintenance plan and a suitable detection method for malfunctioning components are compulsory during operation. This chapter reviews extant literature that explores the current status of heavy-duty conveyor belt structure in the underground coal industry.

The goals of this chapter are to:

- identify conveyor belt characteristics, in comparison to other bulk transport methods, such as trucks or trains
- categorise the variety of designs of conveyor belt structure and review the main components of conveyor belts
- study conveyor belt failure modes and the causes of underground mine fires
- review current monitoring methods and determine the gaps and opportunities for further development.

2.1 CONVEYOR BELT OVERVIEW

Conveyor belts have been widely used for centuries to transport general goods, bulk materials and passengers. Conveyor belts have attained a dominant position in the continuous conveying of bulk materials ranging from very fine, dusty chemicals to bulk materials, such as raw ore and coal, as well as overburden, including stones, soil and logs of wood. In comparison to other transportation methods for bulk solids, such as trains or trucks, conveyor belts are an extremely favourable choice in instances where the suitable infrastructures for other modes of transport do not exist (Pang, 2010).

The advantages of conveyor belts, such as the low cost of equipment, labour, power consumption and maintenance, have made them popular for material handling in the mining industry. Conveyor belts are able to operate continuously with minimum scheduling and dispatching, as the belt itself is able to load and unload the material and empty return trips are not a consideration. In comparison to a diesel engine, electrical power-activated conveyor
belts have higher output energy efficiency and generate less environmental pollution. Minor requirement of operating labour cost and high reliability been proven over decades to reduce the cost of material transport per tonne dramatically (CEMA, 2007).

2.2 TYPES OF CONVEYOR BELTS

Various types of conveyor belts have been designed to outfit different applications. The designs have to consider the capacity requirement, the adaptability to path of travel, the steep angle, and the loading, discharging and stockpiling capacities. Conveyor belts can be classified into the following categories:

- **Conventional trough conveyors** (which are the most commonly used in bulk material transport).

![Figure 2.1. Structure of a conventional trough conveyor (Duncan and Levitt, 1990).](image)

- **Truss-mounted conveyors**, designed based on the conventional trough conveyor for conveyors above grade or platform levels. Both the carry idler and return idler are mounted directly to a box truss framework, allowing them to be used extensively for portable conveyor construction.
- **Portable conveyors**, designed based on conventional trough conveyors (as the name indicates, the conveyors are able to self-move or be towed into different locations across the field).

- **Pipe conveyors**, in which the material is wrapped into a circular shape after loading (five or six idlers are used to wrap the belt into the circle). The materials are totally enclosed and can make horizontal turns with a much shorter radius.
- **Sandwich conveyors**, which use two flat belts to sandwich the material to be conveyed at vertically steep angles.

- **Pocket conveyors**, a sidewall-type conveyor designed to scale high objects, such as a building or a hill. The pockets carry the material so that it does not fall or slide due to the gravity.
In this thesis, the research focuses on the most typical conveyor belt used in the mining industry, which is the conventional troughed conveyor. In order to understand the mechanisms behind the failure of individual components, the structure mechanism of the conveyor belts is described in-depth.

2.3 **MAIN COMPONENTS**

The basic conveyor belt components illustrated in Figure 2.7 include an endless belt that supports and carries the material. The type of belt depends on the material conveyed, tension, loading capacity, operating temperature and any special requirements, some belts for example, may need to be fire resistant. The material used in belts for an underground coal environment is normally rubber-covered polyester or nylon textiles. These materials are highly resistant to corrosion, abrasion and have a melting temperature of above 260°C (Rothery, 2003).
Carry idlers are free rolling components that support the loaded run of the conveyor belts to transmit the materials. Return idlers are located under the conveyor, helping to hold and shape the belt, preventing slippage and maintaining tracking. Troughed idlers usually consist of three idlers, two side idlers (inclined between 20° to 35°) and a horizontal middle idler. Idlers are free rolling components with one bearing located on each end of the idler shaft. The shell covers and seals those elements from external corrosive elements, such as dust and moisture. The impact idler, also called cushion idler, is a standard idler covered with soft material, such as natural rubber, to protect the belt and idlers from damage by falling materials at the loading point.

Idler sets are mounted on the frame structure. One pulley is located at each end of the belt and is powered to rotate the belt and move the material forward. The pulley consists of two end discs fitted with compression-type hubs and a continuous rim. The take-up device is designed to control the tension on the belt, either mechanically or using gravity. The drive unit consists
of an electrical motor, gearbox and the output shaft to supply power to the pulleys and rotate the drive pulley.

2.4 CONVEYOR FAILURE MODE

Major conveyor belt–related mining incidents are now relatively infrequent as a result of recent improvements in engineering standards and the use of fire-resistant materials. However, conveyor belts are still a potential cause of personal and structural damage. In addition, any unexpected breakdown of rolling components or failure of belts creates a significant interruption to production, which is a major concern for operators who are responsible for achieving optimum mining production.

Conveyor belts often suffer from some typical problems during the course of operation. The conveyor system failure modes can be divided into three categories:

- mechanical failure caused by damaged mechanical parts of the machine
- electrical failure caused by damaged electrical parts of the system
- other failure, not directly associated with the machine or its electrical parts (for example, human error).

Gurjar (2012) collected data on and analysed the failure rate of the 20 conveyor belts operating in the Parichha thermal power plant in India. During the period between December 2011 to May 2012, 520 failures occurred. Mechanical failure contributed to 58.1% of the failures with 302 instances recorded. The causes of the mechanical failures are shown in Table 2.1.
Table 2.1. Conveyor belt mechanical failure.

<table>
<thead>
<tr>
<th>Cause of failure</th>
<th>Number of failures</th>
<th>Percentage (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carry idler failure</td>
<td>117</td>
<td>38.7</td>
</tr>
<tr>
<td>Return idler failure</td>
<td>107</td>
<td>35.4</td>
</tr>
<tr>
<td>Pulley bearing failure</td>
<td>19</td>
<td>6.3</td>
</tr>
<tr>
<td>Hammer failure</td>
<td>13</td>
<td>4.3</td>
</tr>
<tr>
<td>Coupling failure</td>
<td>11</td>
<td>3.6</td>
</tr>
<tr>
<td>Belt damaged</td>
<td>9</td>
<td>3</td>
</tr>
<tr>
<td>Sealing damaged</td>
<td>8</td>
<td>2.7</td>
</tr>
<tr>
<td>Gearbox damaged</td>
<td>8</td>
<td>2.7</td>
</tr>
<tr>
<td>Wiper damaged</td>
<td>4</td>
<td>1.3</td>
</tr>
<tr>
<td>Pulley damaged</td>
<td>3</td>
<td>0.9</td>
</tr>
<tr>
<td>Clutch damaged</td>
<td>3</td>
<td>0.9</td>
</tr>
</tbody>
</table>

Source: Gurjar (2012)

From the table, it can be concluded that both carry idler failure and return idler failure are the most common, contributing to 64.1% of mechanical failures. Both Fernandez et al (2013) and Weir (2012) indicate that the majority of roller fail is due to inadequate lubrication (36%), to contamination (14%) or to other causes (16%), such as a worn out idler shell or misalignment. In the normal life of a machine, only 0.5% of bearings are replaced due to bearing failure. In troughed conveyors, side rollers are damaged more easily due to loading variations.

2.5 CONVEYOR BELT FIRES

US Mine Safety and Health Administration (MSHA) has investigated coal mine fires and determined the possible causes of fires in coal mines. The report includes 62 coal fires caused by conveyor belts, which accounted for around 20% in total of the coal fires reported to the MSHA by US coal mine operators in the period between 1980 to 2005. The causes of the fires investigated and the results are illustrated in Figure 2.9. The major ignition source is frictional heat (46%), which can then be divided into friction at the driver unit (18%); friction along the belt (18%) (attributed to friction between the rubber belt, wooden posts, coal dust and spillage) and friction between the idler bearings and the races or the belt or support structure (10%) (Francart, 2006).
The ignition sources of European coal mine fires have been investigated and analysed by Fernandez et al (2013). The study investigated the list of possible ignition sources for conveyor belt fires and the data have been grouped into different countries. Table 2.2 clearly indicates that the main cause of coal fire ignition is associated with the failure of idler sets and bearings.

Table 2.2. Ignition source statistics in percentages.

<table>
<thead>
<tr>
<th>Ignition Source</th>
<th>Denmark</th>
<th>UK</th>
<th>Poland</th>
<th>Ukraine</th>
<th>Australia</th>
<th>USA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Failures in idler sets and bearings</td>
<td>Main reason&lt;sup&gt;A&lt;/sup&gt;</td>
<td>46.7</td>
<td>24.5</td>
<td>Main reason</td>
<td>51</td>
<td>Main reason</td>
</tr>
<tr>
<td>Failures around the drives</td>
<td>6.7</td>
<td>44.4</td>
<td></td>
<td></td>
<td>36</td>
<td></td>
</tr>
<tr>
<td>Failures in alignment</td>
<td>26.7</td>
<td>11.1</td>
<td></td>
<td>13</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Coal spillage</td>
<td>Main reason</td>
<td>13.3</td>
<td>11.1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Other sources</td>
<td>6.6</td>
<td>8.9</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<sup>A</sup> A grey background highlights the main ignition source in conveyor belt fires for each country.

Source: Fernandez et al (2013). This thesis focuses on the evaluation and detection of idler malfunction, therefore understanding the mechanism of idler failure is critical in the improvement of safety in the coal industry.

The UK Health and Safety Executive experimented with dry bearing and found that there are two stages of failure that are able to generate a significant enough amount of energy to trigger catastrophic failure (Hawksworth et al, 2003). Idler rollers with 40 mm bore bearings were selected to meet the British Coal Specification 670:1992. The temperature was recorded by
the inner race thermocouple and a thermal camera. To speed up the bearing failure and remain the trials to be possibly close to reality, the following conditions were applied:

- all lubrication was removed
- conveyor belt in standard speed (3.8m/s)
- axial load overloaded by 25%.

![Graph showing temperature over time](image)

Figure 2.10. First stage failure temperature recorded by thermocouple and thermal camera (Hawksworth et al., 2003).

The first stage of failure is characterised by a steady increase in temperature of the bearing to around 100°C, followed by a slow increase in temperature, before a sudden jump to around 200°C as shown in Figure 2.10. The tests identified that the rapid increase of temperature to 200°C is critical to failure because the temperature indicates the melting of the polyamide roller cage, as shown in Figure 2.11.
The bearing effectively collapses during the second stage of failure. Steel starts to rub against steel: the outer, inner races or shaft make contact with each other, a significant amount of heat is generated in the contact region and the recorded temperature reaches at least 800°C. The temperature exceeds the auto-ignition temperature of methane (595°C), carbon monoxide (609°C) and coal (420°C). In conclusion, the heat generated by the failure of the bearings is sufficiently high to ignite explosive mine fuel hazards.

Other studies have investigated and found the same results: idler failure is an important ignition cause in the underground coal industry. Damaged rollers can increase temperatures from 400°C to 450°C (Zimroz and Krol, 2009). Generally, if a bearing is at least 5°C hotter than the other bearings, this is an indication that it is beginning to fail. Once the bearing fails, its temperature quickly rises by 40–50°C. A collapsed or seized bearing is usually identified at a temperature of 100°C. It must be noted that the rise in roller temperature due to bearing failure varies depending on the type of roller, its location in the mine and mine ventilation conditions (Bradley, 2012). Idler failure temperature varies from site to site, as well as from idler to idler and depends on the conditions of the environment and the life stage of the idler (Murace, 2012). The majority of fires in underground coal mines are a result of seized conveyor belt idler rollers. The rollers can get extremely hot through friction with the running belt or the mechanical failure of bearings.

2.6 Current Monitoring Method

Early fire detection is a tireless topic in the underground coal industry and various types of sensor have been developed and applied in coal mines worldwide. Current conveyor belt monitoring methods are classified in Figure 2.12.
The different types of heat detectors and point sensors listed in Figure 2.12 are commonly used for early fire detection on conveyor belts in the mining industry because the sensors are relevant, low-cost and easy to install. However, to monitor the health condition of idlers in an underground coal mine environment, there are several strict rules that need to be considered. First, the number of idlers that need to be monitored is extraordinarily large: the conveyor belt system can be over ten kilometres and contain over 10 000 idlers. A major issue with conveyor belt monitoring is that every idler bearing needs to be routinely checked, either acoustically or thermally (Brown, 2012). Second, self-battery point sensors require proof of robustness and constant maintenance, which raises the capital and operation cost dramatically. Finally, and most importantly, the prevention of the conditions that allow fires to occur is more effective than determining and extinguishing fires that have already occurred and already caused damage to infrastructure and disruption to operations. Therefore, continuous condition-monitoring methods are preferred.

An intrinsically safe thermal camera is a potential option for continuous temperature monitoring. Given the application conditions, the technical difficulty of representing full idler bearing failure along conveyor belts is not feasible in terms of both safety and cost. Currently, coal conveyor belts experience frequent idler failure and consequent interruptions to maintenance schedules (Down, 2012). Conveyor belts need to be examined for the presence of any overheating, smouldering or unsafe conditions that may interrupt production or cause a fire. Idler failure is one of the most common causes of fire incidents. Periodic inspections of operating conveyor belts are conducted with the aim of detecting any local heat sources at an early stage. These inspections include temperature measurements of the driving drum and idlers using handheld temperature sensors, such as infrared cameras. Current methods for monitoring conveyor belt rollers and pulleys include acoustic methods (walk and listen).
thermographic methods and vibration measurements (Thorpe, 2012). In the underground coal industry, up to 50% of conveyor idlers cannot be accessed for temperature measurements using conventional methods (Ismail, 1998).

2.7 SUMMARY

The disadvantages of the current conveyor idler monitoring methods are significant. Both the use of acoustic devices or thermal camera monitoring methods require experienced technicians to inspect the full length of the conveyor structure regularly. The cost of labour is substantial given that the operation period of an underground mine can span decades, the methods require personnel to be frequently exposed to the hazardous underground environment and, needless to say, there are risks involved with having conveyor structure operating non-stop in an area that is inaccessible to technicians.

An advanced intelligent monitoring system is required in order to overcome the defects in current system, but there are two barriers that must be overcome. First, collecting up-to-date data from conveyor belt components which are highly distributed over a large area is difficult and complex. Monitoring and gathering physical information of the bearings on the idlers requires thousands of sensors on the conveyor belt structure. Second, the transmission, analysis and interpretation of all the collected data is also challenging, especially in an underground coal mine environment where electrical cables are prohibited. A fibre optic-based DTS system using the latest optical fibre technology is an intrinsically safe method that could be the potential solution to solve the problem.
CHAPTER THREE

Distributed Temperature Sensing System
3 DISTRIBUTED TEMPERATURE SENSING SYSTEM

Fibre optic-based sensing technologies are an intrinsically safe method that can potentially be used in underground mine operations to sense a variety of critical parameters. The DTS system has the advantage of being able to take real-time, continuous, long-range and scattered measurements that can be used to monitor the temperature variation of rolling components on conveyor belt structures. This review of the extant literature is designed to explore the theoretical foundation of fibre optic sensing technologies and investigate the gaps and opportunities of current applications of DTS monitoring systems on conveyor belts.

The aims of this chapter are to:

- review the development and explore the fundamental theory of fibre optic sensing technologies
- categorise the variety of technologies used in fibre optic-based DTS monitoring systems
- review the application of fibre optic sensing technologies, particularly in the mining industry and identify the gaps and opportunities for further development.

3.1 SENSING TECHNOLOGY

Sensors are compulsory in the contemporary engineering field: gauges are installed wherever there is relevant information to measure a physical quantity (for example, a leveller in fuel tank, a thermometer in a boiler or a vane anemometer in a wind tunnel). A technician is able to go to the gauge and record the data. In some cases, the data acquisition and the display are separated: for example, the fuel tank level on an airplane wing or a temperature measurement inside a diesel engine. Instead of checking the measurement in the gauge’s physical location, the sensor’s response can be transmitted to a central monitoring station by cables. For example, to the airplane cockpit for pilots to read the plane’s statistics or to the central control room on a mine site for the operator to monitor productivity and safety. The sensors are engineered in this way, not only save time in the taking of instrument readings, but also to reduce the risks for humans accessing the data recordings in hazardous areas. In many conditions, point sensing is not enough: for example, strain sensing in a dam or leakage detection in a long-distance oil pipeline. Without taking into account the capital and
maintenance cost, multiple sensors are one way to solve the problem; however, these systems have one common feature: electrical current. In Australia, electronic devices are highly restricted with intrinsically safe standard in the underground coal industry to prevent gas explosions. In this sense, fibre optic-based sensing technology has a great advantage over other distributed sensors because the data are transmitted by optical, rather than electrical, format. In addition, fibre cable is also small and lightweight, is better able to withstand extreme temperatures and is more robust when in contact with aggressive chemicals.

There are many examples of fibre optic-based sensing system applications in the scientific and engineering fields. Consider, for example: crack sensors in bridge condition monitoring to identify cracks beyond 0.15–0.2 mm (Gu et al., 2010); corrosion sensors in concrete structures to monitor the corroding effects on the expansion in diameter of steel bars (Casas and Frangopol, 2001); the structural health monitoring in filament-wound composite marine pile by fibre Bragg grating sensors (Baldwin et al., 2001); the monitoring of the post-tensioning cable by strain sensor using the Brillouin OTDR principle (Gao et al., 2006) and the utilisation of the Raman backscattering principle to measure the temperature in nuclear power plant fuel pools (Ferdinand et al., 2013).

Many different types of fibre optic-based sensing systems have been invented and applied to measureable parameters including stress, strain, gas concentration (Stewart et al., 1998), vibration, humidity (Xu et al., 2013) and temperature. The fibre optic-based sensing technologies can be broadly grouped into two categories:

- **Extrinsic Sensors**, in which the sensors are mounted on the fibre. The sensors read the physical quantity and transmit the corresponding light signal by fibre (the fibre is only used as a medium to transmit data).

- **Intrinsic Sensors**, in which the fibre itself is a sensor that reads the physical quantity. The fibre is therefore not only used for data transmission, but is also the sensing material.

### 3.2 Fibre Optic Structure

An optical fibre cable is a cable containing one or multiple optic fibres. The fibres are transparent and typically made of doped quartz glass—silicon dioxide. The fibres are thin pipes that guide the light passing through from one end of the cable to the other. The light source
can be a light emitting diode (LED) or a laser signal. The light source that passes through the fibre can be switched on and off, it is also possible to change the frequency and amplitude gradually, the light receiver on the other end of the cable is able to receive the light and convert it back to the original digital signal.

The internal reflection of light bouncing off between the interface of the fibre core and the cladding is caused by the refractive index of the cladding being slightly lower than that of the fibre core. The light rays reflect back in the fibre core when they encounter the cladding with a contact angle that is smaller than a critical angle. The light that exceeds the critical angle refracts and is lost into the cladding, as shown by the yellow line in Figure 3.1.

![Figure 3.1. Light propagates though silica step-index multi-mode fibre cable.](image)

**3.2.1 Categories of fibre optic cable**

Based on the different quantity of light allowed to propagate through, optical fibre can be divided into two categories: single-mode fibre and multi-mode fibre.

![Figure 3.2. The only difference between multi-mode fibre and single-mode fibre is the core diameter (Mitschke, 2009).](image)
A typical fibre structure is illustrated in Figure 3.2: the fibre core is circular in shape and is surrounded by a ring-shaped cladding with a diameter of 125 µm. The outer layer coating is designed in different materials to protect the fibre from different application environments.

### 3.2.2 Single-mode fibre

Single-mode fibre has a relatively narrow core of 7–10 µm in diameter. The slim core only allows one path for the light signal to propagate, eliminating the distortion of light pulses overlapping. At the same time, the index of refraction between the core and the cladding is relatively small. As a result of both of these features, the single-mode fibre has the highest transmission speed and the least signal attenuation. Most telephone and communication cables use single-mode fibre, the long-distance application can go up to 100 km.

### 3.2.3 Multi-mode fibre

Multi-mode fibre is typically made with a fibre core diameter of 50–62.5 µm. In comparison to the single-mode fibre, multi-mode fibre is able to allow multiple light rays to propagate through the core along several different pathways simultaneously by bouncing off the interface between the core and the cladding at different reflective angles.

Figure 3.1 illustrated the light propagation through silica step-index multi-mode fibre. One ray of light propagates travelling a direct route and others bounce off the cladding boundary in a ‘zigzag’ shape. The alternative pathways allows groups of light signals to be transmitted simultaneously, however, the signals have different arrival times at the other end of the fibre. According to Venghaus (2012), the difference in arrival time between the slowest mode and the fastest mode can be calculated by the following equation (where L is the length of fibre, NA is the numerical aperture, c is the speed of light and $n_{cl}$ is the refractive index of the cladding):

$$
\Delta t = \frac{L \times NA^2}{2cn_{cl}}
$$

(1)
Silica graded-index multi-mode fibre is designed to avoid scattered arrival times as a result of multiple light signal pathways. The refractive index is the highest at the centre of the core and then gradually diminishes towards the cladding, causing light to propagate more slowly in the middle of the core. The progressive reduction in the refractive index causes the light to propagate in helical curves rather than a ‘zigzag’ shape. The result of the arrangement is that the light in the centre of the core propagates with a shorter path but is slower in speed, while the light at the periphery has a longer path, but is faster in speed, and both arrive at the receiver at the same time.

### 3.3 Fibre Optic-Based Distributed Temperature Sensing System

The fibre optic-based DTS system is an intrinsic sensor, which was invented and developed more than 30 years ago (Hartog, 1983). The fibre optic cable itself is a sensing material that can provide temperature measurements on thousands of points without the need for a local power supply. This feature opens a significant opportunity to detect idler failure in the underground coal industry. A distributed fibre optic sensing system is a real-time, online, continuous temperature measuring system that has certain advantages, including immunity to electromagnetic interference, light weight, small size, high sensitivity, long-distance, large bandwidth, anti-corrosion, anti-combustion, explosion-proof, resistance to ionising radiation and ease in implementing multiplexed or distributed sensors (Hu et al, 2011).

DTS systems consist principally of a mainframe and a fibre optic cable. The mainframe includes a laser source, a pulse generator, an optical module, a photo detector and a microprocessor unit. The fibre optic cable consists of a number of quartz-glass optical fibres that can each be considered a linear temperature sensor. Commercially available DTS systems with ordinary specifications can measure temperature along more than 30 km of fibre optic cable with a spatial resolution of 1 m, accuracy of ±1°C and a resolution of 0.01°C.
DTS systems measure temperature by using fibre optic cables as continuous linear sensors. The principle of temperature measurement by DTS system is generally based on thermal effect-inducing lattice oscillations within the core of the optical fibre, which is made of silicon dioxide with an amorphous solid structure. The light photons interact with the oscillated molecules of optical fibre as it travels through the fibre. As a result of this interaction, the light is scattered back. Detecting and monitoring the back-scattering light is the key point in fibre optic sensing technology.

3.3.1 Fibre optic location sensing detection method

There are two basic principles to location sensing along the cable in fibre optic sensors: Optical Frequency Domain Reflectometry (OFDR) and Optical Time Domain Reflectometry (OTDR)
The principle of OFDR is shown in Figure 3.6: a beat signal produced by the optical interference between a fixed local reference reflection, called a mirror or local oscillator, and the reflection from the device under test (DUT) with a fixed Fresnel reflection. The laser optical signal frequency is swept, as shown in Figure 3.6. Different beat frequencies on the receiver are in response to the reflections at different distances from the DUT. The received beat frequency value is dependent on the distance between the DUT reflection location and the mirror, within a known rate of optical frequency variation. Using the Fourier transform, each frequency corresponds to a distance (Huttner et al., 1999; Passy et al., 1994). The OFDR principle is able to reach a spatial resolution of centimetres, however the spatial distance is limited to 100 metres (Oberson et al., 2000). Therefore, the OFDR is limited to short-distance measuring applications.

In most fibre optic-based intrinsic sensors, the physical quantity is measured by launching a short pulse of light that propagates through the fibre optic cable. A signal receiver is located at
the launch end to measure the backscattered signal generated by the changing density and composition of the media and the molecular vibrations. The time interval between launching the pulse and receiving the backscattered signal provides the spatial information. There are three different types of backscattered signal that can be used for temperature measurement: Rayleigh, Raman and Brillouin.

In the current market, the majority of DTS system manufacturers use Raman scattering technologies due to the simple backscattered signal detection that results in a lower capital cost. Brillouin-based DTS systems have extremely high spatial resolutions, fast response times and can also be used to detect distributed strain measurements; however, only a few manufacturers supply Brillouin-based distributed temperature and strain sensing systems due to the high cost of the backscattered receiver. Rayleigh-based DTS systems are less popular in the present commercial market because of their short measurement range and instability.

3.3.2 Principles of Rayleigh backscattered light

Rayleigh backscattered light is defined as a two-photon process that has a net effect of hanging the guided direction of scattering light while keeping its frequency constant. Rayleigh scattering is considered to be elastic because the photon energies of the scattered photons remain unchanged. The signal is easy to detect due to the composition fluctuations and the wavelength remains the same as that of the primary laser pulse. In OTDR, the Rayleigh scattering signal can be used to identify any loss, breaks or inhomogeneity along the length of the fibre.

Preliminary studies in fibre optic-based DTS systems were initiated by using OTDR technology to measure the Rayleigh backscattered light in liquid-filled fibres (Hartog, 1983). The liquid core fibres were filled with an ultra-transparent liquid with a high refractive index. The first tests reached 1°C sensitivity at 100 m, with a spatial resolution of 1 m. However, the liquid fibres have issues with long-term durability and it is possible for a void to form under cooling conditions causing the receiver to be unable to distinguish signals as temperature variation or contamination.

More recently, Sang et al (2008) implement polarisation-diverse swept-wavelength interferometry to measure both the phase and amplitude of Rayleigh backscattered light in single-mode silica fibre. The tests reached temperature sensitivity as precise as 0.6% full scale with a spatial resolution of 1 cm, however, the measuring distance is only up to 2 m.
3.3.3 Principles of Brillouin backscattered light

Brillouin backscattering is caused by the light propagating through a medium that interacts with the variations of density. This is associated with changes of the signal’s frequency and wavelength. The variations in density can be acoustic, magnetic or temperature gradients. Brillouin backscattering is technically difficult to separate and measure as the intensity of Brillouin backscattered light is only a thousandth of the incident light. Brillouin scattering produces both the lower frequencies (Stokes), caused by the molecular energy lost by photons, and the higher frequency (anti-Stokes), caused by the molecular energy gained by photons.

Culverhouse et al (1989) initiated the research into Brillouin scattering as a sensing mechanism in DTS. They simulated Brillouin scattering with a combination of incident light, generated acoustic wave and scattered light waves. In the study, the relationship between Stokes and anti-Stokes modulus of the frequency shift $\nu_B$ is a function of local temperature $T$, as the equation shows below:

$$\frac{d\nu_B}{dT} = \frac{2}{\lambda} \left[ V_A \frac{dn}{dT} + \frac{dV_A}{dT} \right]$$

(2)

Where $\lambda$ is the vacuum wavelength of the propagating light, $n$ is the refractive index of the fibre core and $V_A$ is the velocity of the acoustic wave. Culverhouse et al discovered that the sensitivity of the Stokes frequency to temperature is approximately 5.5 MHz/°C.

The equation can be simplified as:

$$\nu_B = \frac{2nV_A}{\lambda}$$

(3)

As the equation shows, the Brillouin scattering frequency shift depends on both the acoustic wave velocity and the fibre core refractive index. Those two parameter quantity changes correspond to temperature and strain along the fibre cable (Azizan et al, 2012). As demonstrated by Zhang et al (2012), the equation can be further developed to:

$$\nu_B = \nu_{B0} + \frac{\partial
}{\partial\varepsilon} \varepsilon(\mu\varepsilon) + \frac{\partial
}{\partial T} T(°C)$$

(4)

Where $\nu_B$ is equal to the sum of the initial frequency shift and the frequency changed by strain and temperature. The frequency shift of Brillouin scattering is expressed as:
The strain coefficient, $C_{ve}$, and the temperature coefficient, $C_{vT}$, are:

$$C_{ve} = 0.0482 \pm 0.004 (MHz/\mu\varepsilon)$$  \hspace{1cm} (6)

$$C_{vT} = 1.10 \pm 0.02 (MHz/K)$$  \hspace{1cm} (7)

The intensity rate of Brillouin scattering corresponds to strain and temperature:

$$\frac{100\delta I_B}{I_B} = C_{pe} \delta \varepsilon + C_{pT}$$ \hspace{1cm} (8)

The strain coefficient, $C_{pe}$, and temperature coefficient, $C_{pT}$, are:

$$C_{pe} = -(7.7 \pm 1.4) \times 10^{-4}\% (\mu\varepsilon)$$  \hspace{1cm} (9)

$$C_{pT} = 0.36 \pm 0.06\% (K)$$  \hspace{1cm} (10)

### 3.3.4 Principles of Raman backscattered light

Raman backscattered light is caused by thermally influenced molecular vibrations. The backscattered light consists of three spectral components:

1. Rayleigh scattering with incident wavelength

2. Stokes scattering (where scattered photons are diminished in energy by the amount of the vibrational transition energy)

3. anti-Stokes scattering (where the vibrational energy is added to the incident photon energy that has a higher frequency).

The intensity of Raman anti-Stokes $I_{as}$ and Stokes $I_{as}$ are dependent on the local temperature, $T$, given by Bolognini and Hartog (2013) as:

$$I_{as}(T) = K_{as} \times \frac{1}{\exp \left( \frac{\hbar * \Delta \nu}{k * T} \right) - 1}$$ \hspace{1cm} (11)
3.3.5 Distributed temperature sensing system applications in underground mines

Fibre optic cables have been tested in different sensing systems in underground mines. They have been used in environmental monitoring systems as a medium for the transmission of data from underground sensors to the surface (Sen and Datta, 1991). Trials conducted over six months at the El Teniente mine in Chile show evidence that the Brillouin scattering optical time domain reflectometer-based distributed fibre optic strain sensing system could qualitatively detect a deformation in the ventilation tunnel caused by stress distribution imbalance as a result of undercutting and ore extraction (Naruse et al, 2007).

\[ I_s(T) = K_s \times \left\{ \frac{1}{\exp \left( \frac{h \cdot \Delta \nu}{k \cdot T} \right) - 1} + 1 \right\} \]  \hspace{1cm} (12)

Where constants \( K_{as} \) and \( K_s \) are the losses suffered by each position independent signal, \( h \) represents the Planck constant, \( k \) represent Boltzmann constants and \( \Delta \nu \) is the Raman frequency shift. The Stokes to anti-Stokes intensity ratio is used in conjunction with the time of flight of the optical pulses to determine the temperature of the fibre at a given point. The Raman scattered light intensity ratio is a function of local temperature, as shown in the equation:

\[
R(T) = \frac{I_{as}(T)}{I_s(T)} = \frac{K_{as}}{K_s} \exp \left( \frac{h \cdot \Delta \nu}{k \cdot T} \right)
\]  \hspace{1cm} (13)

The performance of a DTS system using a calibration function depends on the geometry and chemical composition of the optical fibre. The calibration function for each individual optical fibre needs to be determined before the measurements are taken, as different optical fibre cables have different specific material properties. The accuracy of fibre-specific calibration is an important parameter that controls the accuracy of DTS measurements.
Based on the fact that the spectrum absorption of methane is unique at a wavelength of 1653 nm, Li et al (2011) have developed and examined the distributed feedback of a laser-based fibre optic multipoint methane monitoring system in the Shenyuan coal mine in China. The system can provide multipoint, remote and online methane concentration measurements. Dubaniewicz et al (1993) investigated the application of a fibre optic-based atmospheric monitoring system in Bureau mine in the United States. The system includes: methane monitoring that can detect methane concentration from 0.2% to 100%; a carbon monoxide monitoring system combined with a low-powered electrochemical cell (powered by 9 V battery) that has obtained linearity relationship with gas concentration and has a sensor response with an error rate of 1.6%. A commercial DTS also been tested and is able to provide early warning for equipment prone to overheating over several kilometres.

An OTDR-based DTS system has been installed in The University of Queensland’s experimental mine in Australia to monitor the underground ventilation environment. Various experimental results proved that the DTS system could scan the entire underground mine and locate any spots of temperature variation during heating and cooling processes. The results also showed that the DTS system is a very cost-effective solution when a large number of measurement points are required (Aminossadati et al, 2010).

Fibre optic-based coal mine and tunnel automatic alarm systems were tested at the Research Institute of Explosion Prevention and Suppression in the Chongqing Branch of the China Coal Research Institute (Zhang et al, 2001; Zhang et al, 2000). The system is based on the OTDR principle with a measurement region of -50°C to +100°C, error margin of ±3°C, a temperature resolution of 0.1°C; an optical fibre spatial resolution of 8 m and a measuring time of 69 s. The ambient temperature in the roadway was 19°C and the natural wind speed was 0.5 m/s.

The probe was made up of an eight-metre optical fibre to investigate the effectiveness of multipoint temperature measurement in a condensed measuring location. The probes were placed under the conveyor belt rollers and the tests investigated the surface temperature of the rollers and the effect of the wind speed on the system. The temperature measurements are listed in Table 3.1.
As a result of the tests, the temperature alarm was set at 40°C (as the flammable point of the belt is 150°C). The tests proved that the fibre optic-based temperature monitoring system is able to monitor conveyor belt fires and locate sources of dangerous temperatures in coal mines.

The DTS system has been tested for use in underground mine conveyor systems. The feasibility of implementing a fibre optic-based DTS system on conveyor belts in underground mines has been investigated by Bunker (2008). A Sentor®101 DTS was used in the experimental study, the specifications are listed in Table 3.2.

### Table 3.1. Temperature measurement results.

<table>
<thead>
<tr>
<th>Wind Speed (m/s)</th>
<th>Surface Temperature of Roller (°C)</th>
<th>System Readout (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>91</td>
<td>24.6</td>
<td></td>
</tr>
<tr>
<td>159</td>
<td>34.2</td>
<td></td>
</tr>
<tr>
<td>0.9</td>
<td>258</td>
<td>78.6</td>
</tr>
<tr>
<td>378</td>
<td>92.6</td>
<td></td>
</tr>
<tr>
<td>58</td>
<td>23.8</td>
<td></td>
</tr>
<tr>
<td>163</td>
<td>31</td>
<td></td>
</tr>
<tr>
<td>1.9</td>
<td>255</td>
<td>60.7</td>
</tr>
<tr>
<td>382</td>
<td>91.1</td>
<td></td>
</tr>
</tbody>
</table>

Table 3.2. Sentor®101 DTS key parameters.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Extent</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fibre Type</td>
<td>50/125 graded-index multi-mode</td>
<td>µm</td>
</tr>
<tr>
<td>Measurement Time</td>
<td>≥10</td>
<td>s</td>
</tr>
<tr>
<td>Temperature Accuracy</td>
<td>±1</td>
<td>°C</td>
</tr>
<tr>
<td>Range</td>
<td>10 to 2500</td>
<td>m</td>
</tr>
<tr>
<td>Temperature Resolution</td>
<td>0.3</td>
<td>°C</td>
</tr>
<tr>
<td>Spatial Resolution</td>
<td>1.3</td>
<td>m</td>
</tr>
<tr>
<td>Temperature Range</td>
<td>-10 to +500</td>
<td>°C</td>
</tr>
</tbody>
</table>


Bunker’s thesis investigated four major aspects regarding the potential issues of DTS system application in underground coal conveyor belts; those research aspects and results were to:

- Determine the heat source power output effects on the DTS measurement through conduction heat transfer. Comparing the temperature reading obtained from the thermocouple and the DTS system shows that the DTS system is able to detect temperature changes at the exact locations along the fibre optic cable.

- Determine the the heat source effect of convection heat transfer on the results produced by the system. The results show that the DTS system is not able to detect temperature changes in convection heat transfer accurately.

- Investigate the effect of a selection of fibre optic cable jackets on the system’s ability to identify temperature changes. Experiments with different cable jackets led to the conclusion that the jacket with higher thermal conductivity provides a more accurate temperature profile.

- Investigate the influence of the presence of coal dust on temperature readings by the system. The results show that the coal dust layer had little effect on the accuracy of the temperature profile.

JPower® (2013) has conducted some commercial case studies on the application of DTS systems for monitoring conveyor belts. APSensing (2010) conducted a number of site trials of
their DTS system to monitor conveyor belts in different applications. They proposed the installation layout of the fibre optic cable shown in Figure 3.8 to detect the hot idlers.

Figure 3.8. Fibre optic cable set-up for hot roller detection (APSensing, 2010).

3.4 SUMMARY

Many studies have shown that fibre optic-based sensing systems are mature technologies that can be applied in many different scientific and engineering fields. The use of a distributed fibre optic sensing system to monitor underground conveyor belts, as opposed to the use of a conventional temperature monitoring system, provides new possibilities, such as real-time monitoring, lower labour costs and improved accuracy and personnel safety. The DTS system provides a continuous profile of temperatures along the cable that is installed in the vicinity of the conveyor belt.

In the review of previous studies of fibre optic-based DTS system applications on conveyor belts, a number of research gaps have been identified. These include:

- a comprehensive study of the temperature profile of idler brackets caused by bearing failure

- a study of fibre optic cable installation configurations on conveyor belts
- DTS field trials on heavy-duty conveyor belts.

These gaps will be addressed as the key areas of study in this thesis.
CHAPTER FOUR

Experimental Set-Up
4 EXPERIMENTAL SET-UP

The equipment and conditions vary between the individual experiments because the aims and specific substances are different. This chapter introduces an overview of the experimental set-up, including the DTS system package, the heat simulator and alternative temperature sensors.

4.1 DISTRIBUTED TEMPERATURE SENSING SYSTEM

The Sentinel DTS-LR system, made by Sensornet in the United Kingdom, is used for the experimental study in this thesis. The standalone system consists of two major parts: a standard PC to record and analyse the data received from the laser source and a measuring unit with optoelectronics detector and amplifier. The system is operated by the built-in software designed by Sensornet. The software interface provides the virtual output to the user who can adjust key control parameters, configure the system and manipulate graphical information.

![Figure 4.1. Sentinel DTS-LR standalone and display (Sensornet, 2008).](image)

The system is packaged in a rack chassis that offers mobile temperature measurement. The laser source is classified as Class 1M. The system is safe under reasonable foreseeable conditions, although the laser beam must not be viewed under any circumstances. The DTS system is designed for measurements with a multi-mode fibre optic cable and the system is able to be connected with one cable; however, the multiple fibre optic cable measurements can be achieved with a multiplexer. The Sensornet DTS multiplexer works under the OTDR operation principle. The system capabilities of temperature measurement are listed in Table 4.1.
Table 4.1. Sentinel DTS-LR key parameters.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Extent</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fibre Type</td>
<td>50/125 graded-index multi-mode</td>
<td>µm</td>
</tr>
<tr>
<td>Measurement Time</td>
<td>≥10</td>
<td>s</td>
</tr>
<tr>
<td>Temperature Accuracy</td>
<td>±1</td>
<td>ºC</td>
</tr>
<tr>
<td>Max Optical Loss</td>
<td>9.3</td>
<td>dB</td>
</tr>
<tr>
<td>Range</td>
<td>10</td>
<td>km</td>
</tr>
<tr>
<td>Temperature Resolution</td>
<td>0.01</td>
<td>ºC</td>
</tr>
<tr>
<td>Spatial Resolution</td>
<td>1.02</td>
<td>M</td>
</tr>
<tr>
<td>Temperature Range</td>
<td>-20 to 600 (Dependent on sensing cable used)</td>
<td>ºC</td>
</tr>
</tbody>
</table>


The system can be connected with a 10 km graded-index multi-mode fibre optic cable and the temperature and spatial resolutions are 0.01°C and 1.02 m. The operating temperature is between +5°C and +40°C, while the measurement temperature range depends on the performance of the sensing cable.

4.1.1 Fibre optic cable

The Sentinel DTS is specifically designed to use graded-index multi-mode fibre optic cable with a core diameter of 50 µm and a cladding diameter of 125 µm. The plastic coated fibre optic cable was supplied from MSSFibre. The cables are classified into universal distribution and riser cables, which are widely used for indoor and outdoor communication applications. The cable jacket is fungus resistant, UV resistant, water blocked and low smoke zero halogen for fire safety. The specifications of plastic coated cable are listed in Table 4.2.
Table 4.2. Plastic coated cable specifications.

<table>
<thead>
<tr>
<th>Structure</th>
<th>Specifications</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fibre Type</td>
<td>MM 50(OM3)A</td>
</tr>
<tr>
<td>Fibre Number</td>
<td>2 to 48</td>
</tr>
<tr>
<td>Outer Jacket Material</td>
<td>Polybutylene Terephthalate</td>
</tr>
<tr>
<td>Cable Diameter</td>
<td>5.0 mm</td>
</tr>
<tr>
<td>Cable Bending Radius</td>
<td>During Operation: 50 mm</td>
</tr>
<tr>
<td></td>
<td>During Installation: 75 mm</td>
</tr>
<tr>
<td>Operating Temperature</td>
<td>-20°C to +70°C</td>
</tr>
<tr>
<td>Installation Temperature</td>
<td>-10°C to +60°C</td>
</tr>
<tr>
<td>Weight</td>
<td>20 kg/km</td>
</tr>
<tr>
<td>Tensile Load</td>
<td>450 N/100 mm</td>
</tr>
<tr>
<td>Crushing Resistance</td>
<td>1000 N/100 mm</td>
</tr>
<tr>
<td>Attenuation Coefficient @ 850 nm</td>
<td>≤3.0 dB/km</td>
</tr>
<tr>
<td>Minimum Bandwidth @ 1300 nm</td>
<td>≥1500 MHz</td>
</tr>
</tbody>
</table>

*A 50/125 µm OM3 type multi-mode fibre Source: MSSFibre (2012).*

The steel-armoured cable was purchased from Jubatus. The armour wires and metal tube are used as an outer jacket to provide robust protection for the fibres from the outside environment. The fibres are the same as the plastic coating cable; however, the physical properties are increased significantly with the metal protection shown in Figure 4.3.
Table 4.3. Steel coated cable specifications.

<table>
<thead>
<tr>
<th>Structure</th>
<th>Specifications</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fibre Type</td>
<td>MM 50(OM3)</td>
</tr>
<tr>
<td>Fibre Number</td>
<td>4</td>
</tr>
<tr>
<td>Outer Jacket Material</td>
<td>Armour Wires</td>
</tr>
<tr>
<td>Cable Diameter</td>
<td>2.12 mm</td>
</tr>
<tr>
<td>Cable Bending Radius</td>
<td>During Operation: 33 mm</td>
</tr>
<tr>
<td></td>
<td>During Installation: 132 mm</td>
</tr>
<tr>
<td>Operating Temperature</td>
<td>-25°C to +150°C</td>
</tr>
<tr>
<td>Weight</td>
<td>16.5 kg/km</td>
</tr>
<tr>
<td>Attenuation Coefficient @ 850 nm</td>
<td>≤2.7 dB/km</td>
</tr>
</tbody>
</table>

Source: Jubatus (2012).

Figure 4.3. Structure of steel coated cable (Jubatus, 2012).

4.1.2 Connectors

The fibre optic connectors are capable of connecting and disconnecting the optical fibres with the DTS system. The protruding ferrule guides the connection between the optical fibre and the detector with the more rugged connection surface. The bore of the ferrule fits precisely with the optic fibre cladding. The E2000 connectors shown in Figure 4.4 are used in the Sentinal DTS system. The E2000 is an angle-type connector that protects the system from damaging back reflections.
4.1.3 Splicing

The fusion splicer *FSM-60S*, made by Fujikura, has been used to splice the fibre optic cables and connectors. Breakages in the fibre optic cable are serious problems in the consideration of the installation lengths in underground coal mines. Splicing is the least time-consuming and costly method to repair and re-join the fibre optic cables. The splicer provides total splice attenuation of 0.01 dB, which does not significantly affect the overall system attenuation.

In the early experimental study stage, the plastic coating cable’s four optical fibres were spliced together, forming a continuous fibre as shown in Figure 4.6.
4.2 HEAT SIMULATION

4.2.1 Heat lamp

The infrared heat lamp model HLX Warm Zone, made by Thermal Electric Elements Australia, was used in the heat transfer experiments. The heat lamp, with a power of 1500 W and a heating area of 30 cm by 12 cm, simulated the heat generated by a faulty idler. During the experiments, the heat lamp was connected to an adjustable resistor to simulate different levels of heat generation during the various failure stages of idlers.

4.2.2 Simulation of faulty idler

The processes of the simulation of a faulty idler were carried out using different stages of simulation methods. The rollers were heated in proximity to the bearings at three different locations: A, B and C, using different heating simulation methods.
4.2.2.1 Heat Gun

The heat gun model HG6020, made by Makita, was used in the initial site trials. The output power of the heat gun is 2000 W and the air temperature is adjustable from 50°C to 600°C. The heat gun was used to heat different idler locations in order to simulate the heat generated by potential bearing failure.

4.2.2.2 Glow Plug

The OPF-119 glow plug, made by Bosch, was used as the heat generator. A Powertech unit was used to control the temperature of the glow plug in the range between the ambient temperature and 200°C. In the majority of the tests, the temperature was set at 100°C, which represents the critical temperature of a faulty idler, according to previous studies.
A series of tests was conducted to examine the temperature distribution of the roller end-brackets, while the glow plug temperature was set at 100°C. Figure 4.11 shows the installation images of the glow plug at three different roller locations (A, B and C), as well as thermal camera images of the temperature distribution for each installation. The thermal camera images show that the core temperature of the glow plug was 100°C; however, the temperature decreases as the distance of the measurement point from the core temperature increases.

**Figure 4.11. Installation of Bosch glow plug at three different locations on the rollers.**

### 4.3 Alternative Temperature Sensors

In the experimental study, the temperature output measured by the DTS was compared with the temperature obtained from other temperature sensors for cross-validation of the experimental results.


4.3.1 *Thermal camera*

The FLIR i5 thermal camera was utilised to map the temperature distribution during this experimental study. The temperature accuracy calibrated within ±2°C, the optimised temperature range is from -20 to +250°C and the thermal sensitivity of the system is less than 0.1°C (FLIR, 2012).

![FLIR i5 thermal camera](image1)

Figure 4.12. FLIR i5 thermal camera.

4.3.2 *Thermocouple*

The HC981 thermocouple, made by P.A.Hilton, was used as a point sensor to cross-validate the temperature measurement. The thermocouple is made from nickel, chrome and aluminium alloy (P.A.Hilton, 2005) and is classified as a Type K thermocouple. The thermocouple provides a temperature measurement range from -100 to +1250°C with ±1.1°C temperature tolerance (Wang and Starr, 1991).

![P.A.Hilton HC981 thermocouple](image2)

Figure 4.13. P.A.Hilton HC981 thermocouple.

4.4 *SUMMARY*

In this research, laboratory and site experiments will be conducted. For the laboratory experiments, the following equipment will be used:
DTS system. Sentinal DTS-LR system, measuring distance from 0 to 10 km.

Plastic coated fibre optic cable. MSSFibre multi-mode OM3.


Splicer. FSM-60S fusion splicer.

Heat lamp. HLX Warm Zone heat lamp, 1500 W.

Glow plug. Bosch OPF-119, temperature range from ambient to 200°C.

Thermal camera. FLIR i5 optimised temperature range from -20 to +250°C.

Thermocouple. P.A.Hilton HC981, optimised temperature range from -100 to +1250°C.

For the laboratory experiments, the following equipment will be used:

DTS system. Sentinal DTS-LR system, measuring distance from 0 to 10 km.

Plastic coated fibre optic cable. MSSFibre, multi-mode OM3.


Heat gun. Thakita HG6020, 2000 W.

Glow plug. Bosch OPF-119, temperature range from ambient to 200°C.

Thermal camera. FLIR i5 optimised temperature range from -20 to +250°C.
CHAPTER FIVE

System Characterisation
5 SYSTEM CHARACTERISATION

The DTS system has numerous characteristics to take into consideration before identifying the potential location and developing the criteria for the installation of the fibre optic cable on the conveyor belts. The characteristics of the system are examined here in order to understand the behaviour of the temperature measuring principle and to identify potential difficulties in real applications.

The goals of this chapter are to:

- Investigate the temperature measuring principle of the system with regard to the convection-dominated heat transfer method and the conduction-dominated heat transfer method.

- Study the various potential parameters that could affect the temperature measurement profile. These parameters include sampling time, the bending of the fibre optic cable and the length of the cable exposed to the heat source.

- Propose a cable holder design to improve the system temperature measuring performance with respect to the conveyor idler frame installation.

5.1 HEAT TRANSFER EFFECT

5.1.1 Experimental set-up

The plastic coated cable consists of four optic fibres that are spliced together to form a continuous fibre of 1600 m. The experimental set-up of the heat transfer effect tests are shown in Figure 5.1. The experiments were conducted in two stages. First, the cable was installed at varying vertical distances above the heat lamp in order to examine the system performance with regard to the convection-dominated heat transfer method. In the second stage, the cable was installed on a metal plate at varying horizontal distances from the heat lamp to investigate the performance with respect to the conduction-dominated heat transfer method.
Figure 5.1. Schematic diagram of the heat transfer experiments.

5.1.2 Convection heat transfer

In the convection heat transfer experiment, the fibre optic cable was mounted on a frame with a width of 80 cm and positioned at seven different distances with 10 centimetres apart, ranging from 5 cm to 65 cm above the heat lamp located at the bottom of the frame (as shown in Figure 5.2). The heat lamp voltage set to 40 V. The heat generated by the heat lamp is assumed to be largely transferred through the air via convection. An extra 5 m of cable was left on the side at each line of the cable to separate the measurement of hot regions from individual temperature signal. The temperature profile along the cable was measured by the spliced-together optical fibres.

Figure 5.2. Convection heat transfer experimental design.

Figure 5.3 illustrates the raw temperature data in the convention experiments. The temperature profile along the 1600 m of fibre cable consists of the mirror image of the four
400 m optical fibres, with good repeatability of the temperature measurements. The DTS temperature measurement is to present the average temperature over every 1 m length of fibre. Since the centre of each metres measuring profile of different optical fibres across the frame’s 80 cm width were not aligned vertically above the heat lamp, the variation in the temperature profile was obtained by different optical fibres.

Figure 5.3. Convection experiment raw temperature data.

Figure 5.4. Temperature measurements by DTS versus RTD and thermometer for convection.
The temperature profile comparison between the convection-dominated heat transfer method measured by the DTS system and the average temperature measurements taken by the thermometer and the thermocouple at different distances from the heat lamp is demonstrated in Figure 5.4. The temperature measuring principle of the thermocouple and the thermometer is to measure and present the maximum point temperature along the vertical mid-section of the frame at the centre of each optical fibre cable line. In contrast, the DTS system measures the average temperature profile along 1 m of the optical fibre cable.

5.1.3 Conduction heat transfer

During this stage of the experiments, the fibre optic cable and heat lamp were mounted horizontally on a stainless steel plate that was 1200 mm in width, 1200 mm in length and had a thickness of 1 mm, as shown in Figure 5.5. The cable was positioned in a similar way to the previous case, with seven different distances ranging from 5 cm to 65 cm away from the heat lamp. At the end of each line, an extra 5 m cable was left on the side to separate the measurement of the hot regions clearly.

Figure 5.5. Conduction heat transfer experimental design.
Figure 5.6. Raw temperature data for conduction.

Figure 5.6 illustrates the raw temperature data along the 1600 m of optical fibre in the conduction experiments. The four temperature profiles observed in this graph are captured by the four optical fibres in the cable. The peak temperatures in each profile are associated with the average temperature along 1 m of the fibre. It is clear that due to heat dissipation, the maximum temperature decreases as the distance from the heat lamp increases. Figure 5.7 shows the temperature measurements by one of the fibres in comparison to the average temperatures measured by the thermometer and the thermocouple.
Figure 5.7. Temperature measurements by DTS versus RTD and thermometer for conduction at 40 V.

Figure 5.8. Temperature measurements by DTS versus RTD and thermometer for conduction at 60 V.

Figure 5.8 presented the results with a higher heat power output. The heat power was increased from 40 V to 60 V. It is clear in both scenarios that the DTS system was able to detect the hot spots at different distances. It is also clear that the DTS temperature measurements are lower than the measurements taken by the thermometer and the Resistance Temperature Detector (RTD), especially at distances closer to the heat lamp. As mentioned earlier, this is because the DTS measures the average temperature over 1 m length of the fibre (Bennett, 2013), whereas the other sensors measure the maximum local temperature along the
centreline of the plate. Similar observations were also reported by Bunker (2008) and APSensing (2010).

5.2 FLUCTUATION OF TEMPERATURE MEASUREMENTS

The DTS system principally measures the average temperature over the period of sampling time in which the data are collected by the system. The accuracy of temperature measurements depends on this measuring time. It was necessary to identify an optimum measuring time in which the best accuracy for the temperature measurements could be obtained, while the total time of the experiment was minimised. Figure 5.9 shows the results of the average temperature measurements by the DTS system at different measuring times from 15 seconds to 60 minutes. It is clear that the higher temperature fluctuations correspond to the shorter measuring times. The measuring time of 60 minutes provides a temperature fluctuation of 0.1°C, which corresponds to the DTS system specifications. It was found that, as the measuring time increases above three minutes, the fluctuation drops dramatically. Therefore, a measuring time of three minutes was selected for this experiment to ensure a high degree of accuracy within a minimal measurement time.

5.3 BENDING OF FIBRE OPTIC CABLE

In real conveyor belt application, fibre optic cable bending is inevitable during cable installation on the conveyor frame. The bending of the cable can cause the propagating light signal to exceed the critical angle, refract and be lost into the cladding as per the detailed discussed in Section 3.2. This stage of the experiment focused on the effects of fibre optic cable bending on the performance of the DTS. The aim was to determine the minimum
bending radius of the cable that would not affect the accuracy of temperature measurements. The fibre optic cable was tested with a bending angle of 180° with regard to the bending radius \( r \) (shown in Figure 5.10) from a minimum of 3 cm to a maximum of 10 cm.

![Figure 5.10. Bending of fibre optic cable experiment schematic diagram.](image)

Figure 5.11 shows that the minimum acceptable bending radius was 7.5 cm. This means that the energy loss of light through the cable was significant and that the DTS temperature measurements encountered a noticeable error for bending radiiuses of less than 7.5 cm. The cable manufacturer datasheet also supported the fact that the fibre optic cable performs well with a minimum bending radius of 7.5 cm. The significance of this test was in the design and selection of the diameter of round cable holders to ensure that the bending of the cable inside the round cable holders did not cause any laser signal loss.
5.4 **Fibre Optic Cable Length Exposure to Heat**

The fibre optic cable length exposure to heat experiment aimed to investigate the effect of the length of the fibre optic cable that was exposed to the heat source on the temperature measurements. To simplify the test, hot water at a temperature of 64°C was used as a heat source. The ambient temperature was measured as 26°C during the course of the test. Figure 5.12 shows photos of three different tests in which fibre optic cables with lengths of 10 cm, 1 m and 3 m were inserted in the hot water.

The temperature measurements taken by the DTS system (shown in Figure 5.13) show that the fibre optic cable with an exposure length of 10 cm measured the water temperature as 32°C. This is because only 10 cm of the 1 m temperature-sensing length of the cable was submerged in the hot water. In the second test, when the exposure length was increased to 1 m, the temperature reading increased to 52°C. The explanation for this reading is that a
portion of the 1 m temperature-sensing length of the cable was in the water and the other portion was in the ambient air, resulting in an average temperature of 52°C. In the last of the tests, the exposure length was increased to 3 m. This resulted in an accurate measurement of the hot water temperature by the DTS system as 63°C because this arrangement ensured that a whole 1 m of the temperature-sensing length of the cable was submerged in the hot water.

![Graph showing temperature measurements with different fibre optic cable length exposure.](image)

Figure 5.13. Temperature measurements with different fibre optic cable length exposure.

The results of this test suggest that, for the conveyor belt installation of the fibre optic cable, the exposure length of the cable to the heat source should be greater than 1 m. However, it must be noted that there will be a trade-off between the simplicity of cable installation and the accuracy of temperature measurements.

In the next step, the fibre optic cable was installed on the end-brackets of the roller at location A, with four different exposure lengths: straight, one loop, two loops and three loops, as shown in Figure 5.14. The ambient temperature throughout the test was 20°C. The average temperature of the end-bracket at the location of the cable was measured by the thermal camera as 28°C, while the glow plug core temperature was set at 100°C. The results of the DTS temperature measurements show that, as the exposure length of the cable increased, the measured temperature approached the actual temperature of the end-bracket. However, it must be noted that even with a straight cable installation, where only a small portion of the temperature-sensing length of the cable was in contact with the end-bracket, the DTS system was capable of identifying the hot region.
5.5 Fibre Optic Cable Holders

5.5.1 Design

Multiple factors must be considered in an underground mine environment, such as the presence of coal dust, humidity and ventilation effects, and special accessories have been designed to handle these considerations. The effect of the underground environment are discussed and examined in Section 6.5, Section 6.9 and Section 6.10 in Chapter 6.

Figure 5.15 shows three cable holders of different shapes that were designed by author and manufactured in UQ mechanical workshop for the proper installation of the fibre optic cable on the roller end-brackets. The design criteria were to maximise the heat transfer from the end-brackets to the cable, to insulate the cable from the conveyor belt environment and to protect the cable from any potential damage. Figure 5.15(a) shows the straight cable holder, in which 13 cm of the fibre optic cable was attached to the end-brackets with straight installation. Figure 5.15(b) shows the grooved cable holder, which could accommodate up to 1 m of the cable. In both the straight and grooved cable holders, the cable was directly attached to the end-bracket on one side and was thermally insulated from the environment by the cable holder, which had low thermal conductivity. Figure 5.15(c) shows the round cable holder, which could also hold approximately 1 m of the cable. The round cable holder comprised a section with high thermal conductivity, which held the cable and was attached to
the end-bracket, and another section with low thermal conductivity that thermally insulated the cable from the environment.

![Cable holders: (a) straight, (b) grooved and (c) round.](image)

**Figure 5.15.** Cable holders: (a) straight, (b) grooved and (c) round.

### 5.5.2 Thermal performance

A number of tests were conducted to examine the thermal performance of the three cable holders. The temperature profile of the fibre optic cable attached to the end-brackets of the roller at location A was measured when the glow plug temperature was set at 100°C with heat contribution reaches equilibrium stage. A sample of the results is presented in Figure 5.16. It is evident that the round cable holder displayed the best thermal performance, with the maximum temperature signature.

The complexity of the holder installation is another important criterion. In a comparison between the installation of the grooved and round holders, the round holder is able to be attached to the end-brackets of the conveyor belt before the installation of the fibre optic cable. The grooved holder requires the simultaneous installation of the cable and the holder. In contrast, the straight cable holder had minimum installation space and procedure
requirements. However, it must be noted that the straight cable holder also displayed the worst performance in terms of the accuracy of temperature measurements, due to the limited length of the cable exposed to the heat source. As a result, both the straight and round cable holders were considered in the next stages of the study.

![Figure 5.16. Thermal performance of different cable holders.](image)

5.5.3 Thermal response to variations in temperature

In all of the previous tests, the rollers were consistently heated to a temperature of 100°C using the glow plug. As mentioned earlier, this temperature was selected because it is considered an indication of the beginning of the breakdown process of rollers (Bradley, 2012). However, it is important to understand how the proposed cable installation will respond to different roller temperatures. Therefore, a series of tests was conducted with the aim of investigating the thermal responses of cable holders to varying roller temperatures. In these tests, straight and round cable holders were installed simultaneously at location A on the end-bracket (shown in Figure 5.17). The ambient temperature was maintained at 28°C and the glow plug temperature was varied from 33°C to 100°C. A waiting period of 30 minutes was introduced between each test so that the heat transfer in the end-bracket could reach equilibrium.
Figure 5.17. Installation of straight and round cable holders on the end-bracket.

Figure 5.18 shows the results of the thermal response of straight and round cable holders to temperature variations in the glow plug installed on the roller at location A. In general, the results show that both straight and round cable holders reflect the variations in the glow plug temperature for all temperature levels. However, it is evident that the round cable holder responds more quickly to temperature variations in the roller due to the longer length of the fibre optic cable exposed to the end-bracket.

Figure 5.18. Thermal responses of cable holders to temperature variations in the roller.
5.5.4 Selection of materials

In the previous experiments, aluminium was used for the round cable holders because of its low cost and high thermal conductivity; however, it is important to consider that the use of aluminium in Australian underground coal mines is limited due to the fact that friction could easily cause a spark. Therefore, it was necessary to examine the thermal performance of other materials for the round cable holders.

Figure 5.19 shows the installation of three round cable holders, made of aluminium, copper and steel respectively, as well as thermal camera images of the temperature distribution of these installations. The raw material of steel is relatively low-cost; however, the thermal conductivity of steel is only a quarter of that of aluminium. Copper has the highest thermal conductivity of the three materials; however, the raw material is expensive.

The thermal images show the heat distribution in equilibrium stage, the metal plate surface areas of aluminium, copper and steel only have a difference of 0.2°C. It is evident that the three metals provide very close temperature measurements during the equilibrium stage.

![Installation of round cable holders made from different materials](image)

Figure 5.19. Installation of round cable holders made from different materials.

Figure 5.20 presents a comparison between the thermal performances of the three cable holders. It is clear that the three different types of material eventually reach the same
temperature after 30 minutes. However, the greater rate of temperature increase in relation to the response time indicates the material with the higher thermal conductivity. Copper has the best thermal response time, but is the most expensive. Taking into consideration the cost and the thermal response time of the three materials, steel was considered the best choice for the round cable holders.

![Temperature profiles of round cable holders made from different materials.](image)

**5.5.5 Effect of the heat transfer areas**

In the initial design of the round cable holders, the heat transfer area between the end-bracket and the cable holder was 19.6 cm², as shown in Figure 5.21(a). Theoretically, it is clear that, as the heat transfer area increases, the rate of heat transfer increases and the temperature measured by the DTS system thus reaches the temperature of the roller end-bracket more quickly. In this part of the tests, a new round cable holder with an increased heat transfer area of 55.9 cm² was designed and manufactured, as shown in Figure 5.21(b).
Figure 5.21. Round cable holders with two different heat transfer areas.

Figure 5.22 presents the temperature variation of the end-bracket using the two round cable holders with different heat transfer areas. The results show that the round cable holder with the larger heat transfer area reaches the peak temperature after 10 minutes. For the round cable holder with the smaller heat transfer area, it takes 30 minutes for the temperature to reach a steady state. For future tests, it is recommended that round cable holders with a greater heat transfer area be used, to increase the heat transfer rate and reduce the measurement time.

![Heat Transfer Area](image)

Figure 5.22. Temperature variations of round cable holders with different heat transfer areas.

**5.6 SUMMARY**

The present study aimed to conduct a series of laboratory experiments to examine the performance of the DTS system in response to the effect of heat transfer methods, temperature-reading fluctuation in relation to sampling time, the effect of cable bending, the
effect of length of the exposed cable to different heat sources and the cable holders’ design and improvement.

The heat transfer experiments measured the temperature at different distances from a heat lamp that simulated a heated faulty idler. Two different heat transfer mechanisms, convection and conduction-dominated regimes, were investigated and the results were compared against the temperature measurements by a thermometer and RTD. It was found that the DTS system was capable of detecting the hot spots at different distances from the heat lamp; however, it was noted that the DTS temperature profile measurements had clear limitations as a result of the principles of temperature measurement by the DTS system. That is to say, the length of the heated region in relation to the spatial resolution of the DTS should be taken into consideration when DTS systems are used to measure temperature profiles accurately.

The length of exposed cable experiments, using hot water and idler end-bracket tests, clearly identified that there will be a trade-off in real installations between the simplicity of cable installation on the idler end-bracket and the intensity of the temperature signal received. The cable holders were designed based on the results of previous tests. The diameter of the round and grooved holders were selected for the minimum bending radius of the cable. The holder is able to isolate the cable from an underground coal environment and can provide longer cable contact length if required.
CHAPTER SIX

Site Experiments
6 SITE EXPERIMENTS

The mechanical components of conveyor belts normally create heat and/or noise when they encounter functional failures. Currently, in the majority of conveyor belt installations, these failures are identified through routine inspections by site personnel using thermal and/or acoustic handheld devices. These inspections have proved to be costly and unreliable, and may also expose personnel to safety hazards. A fibre optic-based monitoring system using a DTS system has the potential to provide real-time, accurate and low-cost measurements of temperature profiles along the conveyor belt and to identify any mechanical failures at an early stage. The challenge is to determine how the cable should be installed to maximise the system’s sensitivity to heat generated by malfunctioning components.

The aim of this chapter is to:

- Investigate a variety of cable installation layouts and determine the most efficient installation configuration.
- Examine the performance of round and straight cable holders in on-site trials.
- Investigate the potential parameters that may affect the DTS temperature reading, such as the length of the exposed cable, the vibration of the conveyor system while in operation, ventilation in the mine and the amount of light during day or at night.

6.1 LOCATION OPTIONS FOR THE FIBRE OPTIC CABLE

Figure 6.1 shows the possible locations for fibre optic cable installation that rely mainly on conduction and convection heat transfer. There are several applications of a DTS system in underground mine roadways where the cable is installed along the convection heat transfer area; however, the main purpose is for environmental monitoring and fire detection (APSensing®, 2010; JPower®, 2009).
6.2 **Fibre Optic Cable Installation Layout Options**

Figure 6.2 shows fibre optic cable installation layout options that rely mostly on conduction heat transfer from the hot end-bracket to the fibre optic cable.

Table 6.1 presents the advantages and disadvantages of each installation layout option.
Table 6.1. Advantages (+ve) and disadvantages (–ve) of each installation layout (L) option.

<table>
<thead>
<tr>
<th>Layout option</th>
<th>Advantages and disadvantages</th>
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</thead>
<tbody>
<tr>
<td>L1</td>
<td>• easy installation</td>
</tr>
<tr>
<td></td>
<td>• easy access for future maintenance</td>
</tr>
<tr>
<td>+ve</td>
<td>• able to detect temperature change at location A on one side of the idler</td>
</tr>
<tr>
<td>–ve</td>
<td>• bending issue at one end of installation</td>
</tr>
<tr>
<td></td>
<td>• unable to detect temperature change at B and C</td>
</tr>
<tr>
<td>L2</td>
<td>• able to detect temperature change at A, B and C</td>
</tr>
<tr>
<td></td>
<td>• difficult installation, maintenance and repair</td>
</tr>
<tr>
<td>–ve</td>
<td>• requires excessive cable length</td>
</tr>
<tr>
<td></td>
<td>• bending issue at each end of installation</td>
</tr>
<tr>
<td></td>
<td>• cable is prone to damage</td>
</tr>
<tr>
<td>L3</td>
<td>• able to detect temperature change at A, B and C</td>
</tr>
<tr>
<td></td>
<td>• able to detect temperature change along the idler frame</td>
</tr>
<tr>
<td></td>
<td>• difficult installation, maintenance and repair</td>
</tr>
<tr>
<td>–ve</td>
<td>• requires excessive cable length</td>
</tr>
<tr>
<td></td>
<td>• bending issue at each end of installation</td>
</tr>
<tr>
<td></td>
<td>• cable is prone to damage</td>
</tr>
<tr>
<td>L4</td>
<td>• easy installation</td>
</tr>
<tr>
<td></td>
<td>• easy access for future maintenance</td>
</tr>
<tr>
<td>+ve</td>
<td>• able to detect temperature change at location A on both sides of the idler</td>
</tr>
<tr>
<td>–ve</td>
<td>• requires DTS multiplexer for multi-fibre optic cable installation</td>
</tr>
<tr>
<td>L5</td>
<td>• able to detect temperature change at A, B and C</td>
</tr>
<tr>
<td>–ve</td>
<td>• requires DTS multiplexer for multi-fibre optic cable installation</td>
</tr>
</tbody>
</table>

### 6.3 End-Bracket Tests

The initial site trial of the DTS monitoring system was conducted on a roof-covered section of the CV08 conveyor belt at the Queensland Bulk Handing (QBH) site in Port of Brisbane. A schematic diagram of this installation is presented in Figure 6.3. The aim of the initial site trial was to examine the performance of the DTS monitoring system with layout option L1 in detecting the hot idler when the idlers were heated separately at locations A, B and C.
Figure 6.3. Schematic diagram of first site trial of the DTS monitoring system (layout option L1).

Figure 6.4 shows a photo of the first trial of the DTS monitoring system. The fibre optic cable was installed on the steel end-brackets of rollers by clamps at location A. The ambient temperature was 32°C and one of the rollers was heated to a range of temperatures (35°C, 67°C and 100°C) using a heat gun.

Figure 6.5 presents the transient trend of DTS temperature measurements when the fibre optic cable was installed at location A. The results generally show that the system was capable of detecting the hot roller when the temperature at location A was increased from the ambient temperature of 32°C to higher temperatures of 35°C, 67°C and 100°C. However, it is evident that the DTS system was not able to detect the temperature rise at locations B and C while the fibre optic cable was installed at location A.

Several defects were found in the initial site test that will be improved in later experiments. For example, the result shows noticeable temperature fluctuations, which are due to improper DTS sampling time. In later tests, it is recommended to take temperature measurements over a 3 minute period and then to calculate the average, to improve the quality of the temperature signals. The heat simulation method also requires improvement. The distance between the
fibre optic cable and heated location A on the idler is relatively small and the DTS system is able to detect a temperature increase at the heating location; however, it is impossible to distinguish whether the heat is from hot air generated by the heat gun or from conduction by the heated idler. The glow plug used in later tests to simulate the heat from inside the idler where the bearing is located.

![Graph showing temperature over time for different locations](image)

Figure 6.5. Results of the initial site trials.

### 6.4 LENGTH OF CABLE EXPOSED TO ROLLER END-BRACKET

Figure 6.6 shows photos of three tests that were conducted according to the location of the heat generation in the idler. In each test, four cable installations with different lengths of the fibre optic cable exposed to heat generation were considered. These installations were straight, one loop, two loops and three loops of the cable attached to the end-bracket of one of the rollers.
Figure 6.6. Installation of fibre optic cable with different cable lengths exposed.

Figure 6.7 and Figure 6.8 show the results of the DTS temperature measurements for the various lengths of the fibre optic cable exposed to the end-bracket. The results are presented for two different heat locations, A and C. In general, the DTS system was capable of identifying the heat source for all the different lengths and installations. For both installations, as the length of the cable exposed to heat increased, the temperature signal became stronger. It was also evident that the temperature signal was stronger for location A (as shown in Figure 6.7) than location C (as shown in Figure 6.8), due to the greater length of the cable exposed to the end-bracket in location A.
6.5 Effects of Air Flow

The operation of conveyor belts in underground coal mines is normally influenced by the mine ventilation conditions. One of the main issues with the performance of the DTS monitoring system is the effect of ventilation airflow on the accuracy of temperature measurements. A series of tests was conducted with different airflow velocities over the fibre...
optic cable installation to examine the effect of airflow velocity on the DTS temperature signals.

![Figure 6.9. Effects of airflow test.](image)

The fibre optic cable was installed at location A on the end-bracket using both straight and three-loop configurations. The ambient temperature was 23°C and the temperature of the roller at location A was increased to 100°C. The airflow was generated by an axial fan at three different velocities: 0.7 m/s (natural ventilation), 2 m/s and 4 m/s. Figure 6.10 and Figure 6.11 show the temperature profiles of straight and three-loop cable installations respectively. The results show that when the cable was installed with no insulation from ambient conditions, the airflow velocity significantly affected the DTS temperature signal for both the straight and three-loop cable installations. The results of these tests clearly indicate that, in real applications, only cable holders with a proper insulation mechanism should be employed. The cable holders can insulate the fibre optic cable not only from mine ventilation, but also from other underground mine environmental conditions, such as humidity and coal dust.
6.6 Site Fibre Optic Cable Installation Design

This series of tests was conducted on the CV08 conveyor belt at the QBH site in Port of Brisbane. Figure 6.12 shows the schematic diagram of the DTS temperature monitoring system installed on nine sets of idlers in the roof-covered section. The middle idler, idler 5, was selected as the modified idler to simulate the heat generated by a faulty idler. At different stages of the tests, the middle idler was heated at locations A, B and C to a core temperature of 100°C using a Bosch glow plug that was inserted into the centre of the roller end. Two
fibre optic cables were installed and secured on the conveyor belt frame from idlers 1 to 9. The fibre optic cables were installed on the steel end-brackets as close as possible to the heated locations where the rollers’ bearings located. This was to detect, effectively and quickly, the temperature rise that resulted from the heat build-up in the modified idler in the middle section. At location A, both straight and round cable holders were tested, while at locations B and C, straight cable holders were used due to the fact that the round holder was unable to fit within the limited space. The experiment was based on the end-bracket temperatures as an indication of the heat generated by faulty rollers. Figure 6.13 shows a photo of the installation of the proposed monitoring system.

Figure 6.12. Schematic diagram of fibre optic-based monitoring system installation at QBH.

Figure 6.13. Fibre optic cable installation at QBH.

Figure 6.14 shows a photo of the installation of a round cable holder at location A on the middle idler, which was heated by the glow plug. The photo also shows the fibre optic cable that was attached to the idler end-bracket using the round cable holder. The thermal camera image of the roller shows that the core temperature was 100°C, but that the temperature of the
steel end-bracket, at the location of cable installation, was approximately 38°C. This was the maximum temperature expected to be measured by the fibre optic cable.

Figure 6.14. Round cable holder installation at location A on idlers.

Figure 6.15 and Figure 6.16 present the temperature profile of nine idlers measured by the DTS system, where the middle idler had a relatively high temperature in comparison to the other idlers. The results show that the DTS system was capable of identifying the hot roller with the round cable holder. Figure 6.15 presents the temperature profiles along the nine idlers before and after heating the middle idler to 100°C. The temperature profile before heating represents the ambient temperature profile in the roof-covered section of the conveyor belt. Figure 6.16 shows the gauge temperature profile of the nine idlers. It is evident that the peak temperature corresponds to the middle idler, where the roller was heated. It must be noted that, even though the core temperature of the roller was maintained at 100°C, the maximum measured temperature was approximately 2.5°C higher than the ambient temperature. This corresponds with the thermal camera measurements at the point of fibre optic cable installation on the idler frame.
Figure 6.15. Temperature profiles at location A for idlers 1–9 using a round cable holder.

Figure 6.16. Gauge temperature profile at location A for idlers 1–9 using a round cable holder.
6.7 Straight Cable Holders at Location A

For this test, the round cable holder, which was previously installed at location A, was replaced by a straight cable holder and the experiments were repeated. Figure 6.17 shows a photo of the installation of the straight cable holder at location A on the heated middle idler.

![Figure 6.17. Straight cable holder installation at location A on the idler.](image)

The results presented in Figure 6.18 show that the ambient temperature profile for idlers 1 to 9 for the straight cable holder was similar to that of the round cable holder in the previous experiment; however, the temperature of the middle idler was lower because a shorter length of cable was exposed to the heat. Figure 6.19 presents the profile of the gauge temperature for idlers 1 to 9. It is clear that the DTS system was capable of identifying the heated idler despite the fact that the signal was not as strong as that from the round cable holder.
Figure 6.18. Temperature profiles at location A of idlers 1–9 during conveyor operation.

Figure 6.19. Gauge temperature profile at location A for idlers 1–9 during conveyor operation.
6.8 STRAIGHT CABLE HOLDERS AT LOCATION B–C

This test aimed to examine the performance of the DTS system when the idler was heated to a temperature of 100°C at location B–C. The fibre optic cable was installed at location B–C using the straight cable holder (as shown in Figure 6.20). The thermal camera image shows that, even though the core temperature of the glow plug was set at 100°C, the maximum temperature able to be measured by the DTS system at the end-bracket of the roller was 38°C.

Figure 6.20. Straight cable holder installation at idler location B–C.

The green line in Figure 6.21 demonstrates a similar ambient temperature profile as that observed in previous tests. The temperature profile of the idlers after heating the middle idler shows a relatively high temperature for this idler in comparison to others. The gauge temperature results presented in Figure 6.22 show that the DTS system was capable of identifying the hot roller at location B–C with the straight cable holder.
With the straight cable installation at locations A and B–C, the temperature obtained from the DTS monitoring system in response to the modified idler is weaker than that obtained using the round holder. The gauge temperature profile shows that the temperature signal increase at idler 5 is clearly detectable. Therefore, with the steady fluctuation of the ambient temperature
profile, the DTS monitoring system is able to provide real-time faulty idler monitoring to localise the maintenance area for the site operator.

6.9 CONVEYOR BELT OPERATION

This experiment aimed to examine the performance of the DTS monitoring system with the conveyor belt in operation, as the experimental set-up shows in Figure 6.23. Figure 6.24 presents the temperature profile of the selected idlers measured before and after heating the modified idler while the conveyor belt was in operation. The results shown in Figure 6.25 prove that the DTS monitoring system was able to detect the heated idler location under normal operating conditions. The functional idlers demonstrated a similar temperature to the ambient temperature. However, after idler 5 was heated to 100°C, the temperature profile indicated a peak temperature that corresponded to the modified idler location.

Figure 6.23. Installation of the DTS monitoring system on an operating conveyor belt.
6.10 OVERNIGHT AMBIENT TEMPERATURE PROFILE

The DTS monitoring system was used to measure the ambient temperature profile along idlers 1–9 over a period of time. Figure 6.26 illustrates the ambient temperature variation from 16:00 to 09:30 the next day for idlers 1–9. It is clear that the sunlight radiation on the roof of
the conveyor section generated a temperature profile with a maximum temperature around the middle section where idler 5 was located. After sunset, the ambient temperature distribution was more uniform through the section when the sunlight radiation was eliminated.

The results of this test prove that the DTS monitoring system can be used to examine variations in environmental conditions. Figure 6.27 and Figure 6.28 present the time variation of ambient temperature for all idlers and for idler 5 respectively. The results show that from sunset to sunrise, the ambient temperature is the same around all of the idlers; however, the ambient temperature increases towards the middle idler as the sun’s radiation creates a temperature profile inside the tunnel.

Figure 6.26. Overnight ambient temperature profile along idlers 1–9 in 3D view.
Figure 6.27. Overnight ambient temperature profile along idlers 1–9.

Figure 6.28. Overnight ambient temperature profile along idler 5.
6.11 PROPOSED FIBRE OPTIC CABLE INSTALLATION

A schematic diagram of the proposed fibre optic-based monitoring system is presented in Figure 6.29. The system consists of a DTS system, five fibre optic cables, two round holders and two straight holders for each idler set. Four fibre optic cables connected with the DTS monitoring system are secured on the frame of the conveyor and at each end of the cable holders. The cables are attached to the frame of each idler using round or straight cable holders to increase the rate of conduction heat transfer from the rollers to the fibre optic cables and to insulate from underground mine environmental effects. One extra fibre is installed on the roof of the roadway to monitor the ambient temperature along the conveyor belt and to provide a reference temperature profile for faulty signal validation.

Figure 6.29. Schematic diagram of the proposed fibre optic-based monitoring system.

6.12 SUMMARY

This chapter focused on a series of site trials to determine the most suitable cable installation layout, examine the cable holders’ performance and investigate the possible effect of the underground coal mine conditions on the DTS monitoring system.

The results of the initial site trial showed that the cable installation configuration must cover the side of the conveyor belt’s bearing location, as well as the middle section. Installation L5 was able to cover locations A and B–C with minimum disruption to regular maintenance
work. The trial also led to the improvement of heat simulation methods and a study of the characteristics of the system.

The possible effects of underground mine conditions were examined using ventilation and day/night experiments. It was found that cable holders are compulsory to insulate the DTS monitoring system from the environment and to be able to obtain the detectable temperature signal corresponding to the faulty idler. The system was able to measure the ambient temperature variation to provide a reference temperature profile for faulty signal validation. The fibre optic cable performance test investigated the round and straight cable holders on locations A and B–C and the results show that, with the steady fluctuation of the ambient temperature profile, the DTS monitoring system was able to provide real-time faulty idler monitoring to localise the maintenance area for the site operator.
CHAPTER SEVEN

Conveyor Monitoring during Inertisation
7 CONVEYOR MONITORING DURING INERTISATION

The development of the DTS monitoring system is of considerable significance to the mining industry. The nature of the fibre optic-based system is robust and intrinsically safe to handle in the underground coal mine environment. As the laboratory experiments and site trials in the previous chapters proved, the system is able to detect the conveyor belt idler failure at an early stage to avoid catastrophic failure and replace the continuous labour cost in the long term. Of equal importance, the DTS monitoring system is able to provide a real-time temperature profile of the conveyor belt structure and surrounding area so that the operator can observe the roadway temperature conditions; this helps the operator to make critical decisions in serious situations.

The Kestrel site trials prove that the Conveyor Monitoring Project is able to deliver multiple applications of significance to the mining industry. The Kestrel site trial is an individual Australian Coal Industry’s Research Program (ACARP) project named Inertisation, which was conducted in the Kestrel North coal mine involving the monitoring of the temperature profile of a section of underground conveyor belts using the DTS system.

This chapter aims to:

- Investigate the conveyor belts’ temperature profile in an underground coal environment.
- Monitor the temperature profile along the conveyor structure and the surrounding area.
- Provide a real-time temperature profile along the conveyor drift to help the operator make critical decisions.

7.1 OVERVIEW

7.1.1 Mine site

The Kestrel North underground, long-wall operation coal mine is located 40 km north east of Emerald in central Queensland. The North mine was in operation for the past 22 years; however, due to the fact that the access of the remaining resources is no longer profitable and the rapid increase of underground water levels, the mine closed at the beginning of 2014 (RioTinto©, 2014).
7.1.2 Inertisation process

Inertisation is a technique used to enhance the underground coal mine safety after an outbreak of heat, fire or an explosion event. The fuel, ignitions and oxygen in the atmosphere sustain combustion. The idea of ‘inertisation’ is to reduce the oxygen in the atmosphere to a level that is not high enough to sustain combustion in order to extinguish the fire event. The oxygen can be replaced by an inert gas, such as nitrogen or carbon dioxide, that does not participate in the oxidation or combustion process (Mucho et al, 2005).

The inertisation system used in this project was designed in Poland and is called Gorniczy Agregat Gasniczy (GaG). In this system, gas driven by a SO3 jet engine (shown in Figure 7.2) consumes 90% of oxygen in the combustion chamber. 600 L of water is injected into the afterburner every minute to cool the exhaust gas. The exhaust gas contains up to 84.5% of nitrogen and vapour, with less than 4% oxygen. After the cooling process, the exhaust gas, at 90°C, is discharged into the conveyor drift, then spread to the underground coal mine to extinguish the fire event.

The details of GaG performance and exhaust gas contents are listed in Table 7.1.

Figure 7.1. Inertisation process set-up.
The performance datasheet of the SO3 jet engine is listed in Table 7.2.

<table>
<thead>
<tr>
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<th>Extent</th>
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<td>GaG Output</td>
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<tr>
<td>Nitrogen and Vapour</td>
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<tr>
<td>Carbon Dioxide</td>
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<td>Oxygen</td>
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<tr>
<td>Carbon Monoxide and Hydrogen</td>
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<td>Water Requirement</td>
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<tr>
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Table 7.2. SO3 jet engine datasheet.

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<td>Overall Pressure Ratio</td>
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<tr>
<td>Thrust to Weight Ratio</td>
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</tr>
</tbody>
</table>


Figure 7.3. Diagram of fibre optic cable installation in an underground coal mine.

During the inertisation process, the entire mine is sealed for safety reasons. A limited number of point temperature and gas sensors are maintained inside the mine for data collection; however, the measurements are not continuous and the space between each sensor is over 100 m.

The DTS monitoring system is used to monitor the temperature profile along the conveyor drift, provide real-time temperature data for the operator and monitor the propagation of the injected gas. The conveyor drift is 1000 m long with a decline angle of 14°. The ideal design to monitor the temperature along the conveyor drift would be to use 1000 m of steel coated cable to avoid any damage caused by the 90°C exhaust gas and monitor the entire drift. However, due to the time limitation of preparation, two fibre optic cables were installed on
the conveyor belt structure. A 100 m steel coated cable was installed on the top section of the frame, close to the exhaust duct, and a 400 m plastic cable was installed in the middle section of the structure. At the end of the tests, the 400 m plastic cable survived in the extreme temperature environment and provided an adequate signal and temperature data. Therefore, only the 400 m temperature profile is discussed in the next section.

The project was a cooperation between Simtars, ACARP, Rio Tinto Coal, Queensland Mines Rescue Service and The University of Queensland.

7.2 RESULTS AND DISCUSSIONS

The DTS monitoring system was used to measure the temperature profile along the underground conveyor belt for every 50 m benchmark. Figure 7.4 illustrates the temperature variation from 12:00, when the GaG started, to 20:00. The temperature at the starting point (the 0 m benchmark), increased to 90°C within one minute after the GaG started. The results clearly identify that the peak temperature was reduced and the propagation period increased as the benchmark gets deeper and deeper. This was due to the energy lost during the high temperature exhaust gas spread into the drift and the increase in pressure during the air injection. The GaG stopped at 16:30 and it is clear that the DTS monitoring system detected the temperature reduction along the conveyor drift. The drift temperature slowly reduced to the ambient temperature after the gas injection. The DTS monitoring system discovered a major temperature drop from 250 m onward at 14:30. The reason this sudden temperature decrease was found during an after-test site investigation: it was caused by a compressed air pipe cracking under expansion as a result of the temperature increase.
The significant amount of gas leakage found in the entry of the conveyor drift (as the photo shows in Figure 7.5), caused a major issue for the reduction of the gas propagation period. The leakage was sealed out for Test 2.

Figure 7.5. Gas leakages at conveyor drift entry in Test 1.

Figure 7.6 presents the temperature profile along the 350 m conveyor drift from 09:00 to 14:00. A similar temperature profile was obtained from the DTS monitoring system; however, due to the sealing of the leakage, the temperature increased more quickly to the highest
temperature for each benchmark. The peak temperature at 350 m increased to 80°C, instead of 60°C (as it was during Test 1).

![Figure 7.6. Test 2 temperature profile for every 50 m benchmark.](image)

### 7.3 SUMMARY

The development of the DTS monitoring system is significant in a number of ways for the mining industry. The results of the Kestrel North coal mine test prove that the DTS monitoring system is able to provide a real-time temperature profile of the conveyor belt structure and the surrounding area so that the operator can observe the roadway temperature conditions and make critical decisions in serious situations.
CHAPTER EIGHT

Conclusions and Recommendations
8 CONCLUSIONS AND RECOMMENDATIONS

8.1 CONCLUSIONS

One of the major issues with conveyor belts is the unexpected breakdown of rolling components, which causes significant interruption to production, major damage to surrounding infrastructure and the risk of injury to personnel. The mechanical components of conveyor belts create heat and noise when they encounter functional failures. Site personnel in the mining industry are currently performing routine inspections using thermal/acoustic handheld devices to identify any conveyor belt failures. However, the current routine inspections have proved to be costly and unreliable and may also expose personnel to safety hazards. A fibre optic-based monitoring system using a DTS system has the potential to provide real-time, accurate and low-cost measurements of the temperature profile along the conveyor belt and to identify any mechanical failures at early stages. The challenge is to determine how the cable should be installed to maximise system sensitivity to the heat generated by malfunctioning components. This project aimed to investigate various fibre optic cable installation configurations on a conveyor belt to maximise the reliability of the system and minimise interruption to the operation and maintenance of the conveyor belt.

In this project, a series of laboratory experiments and site trials were conducted to determine the best possible configuration of the fibre optic cable installation. The laboratory experiments included the characterisation of the DTS system performance by measuring the temperature profile of hot idlers. Two different heat transfer mechanisms, of convection- and conduction-dominated regimes, were investigated and the results were compared against the temperature measurements taken by a thermometer and a RTD. It was found that the DTS system was capable of detecting the hot spots at different distances from the heat source when conduction was the main mechanism of heat transfer. It was also noted that the length of the heated region of the cable, with respect to the DTS spatial resolution, had a significant impact on the temperature measurements. It was found that higher temperature fluctuations from the DTS system corresponded to shorter measuring times. As the measuring time increased above three minutes, the fluctuation dropped dramatically. Therefore, a measuring time of three minutes was selected for the site trials conducted in this study to ensure a high degree of accuracy and an acceptable measuring time.
The tests on fibre optic cable bending demonstrated that the loss of energy (light) through the cable became significant, and the DTS temperature measurements began to produce noticeable errors, for bending radiuses of less than 7.5 cm for the tested cable. A series of tests were also conducted on the structure and material of fibre optic cable holders by which the cable was attached to the end-bracket of the rollers. It was noted that, although they had a more complex installation process, the round cable holders offered a higher sensitivity than the straight cable holders in the temperature measurements of hot rollers. The experiments on the materials tested for the round cable holders showed that steel had an acceptable thermal response time and the lowest cost in comparison to the other materials tested.

The site trials began with simple installations of the fibre optic cable alongside the conveyor belt. The effect of air speed on the performance of the DTS system was examined and it was noted that the fibre optic cable must be properly installed on the end-brackets and be insulated from environmental effects. The following series of site trials employed round and straight cable holders and the DTS temperature results were similar to those of the laboratory experiments. It was noted that, by using the cable holders and performing system calibration, the DTS system could be protected from the effects of ventilation, humidity, dust, vibration and ambient temperature variations.

In summary, the fibre optic-based DTS system is able to provide real-time measurements, lower labour costs, higher accuracy and improved personnel safety in the monitoring of underground coal mine conveyor belt systems. Further studies are required to identify the issues associated with long-term site application that take into account the monitoring of other mechanical components, such as the driver pulley and the return idlers. There is also scope for future research into a combination of other fibre optic-based monitoring systems, such as distributed acoustic and vibration sensing systems.

### 8.2 Recommendations

#### 8.2.1 Future research

The aim of this project was to develop a fibre optic-based monitoring system using a DTS system to detect and report temperature changes in faulty idlers for heavy-duty conveyor belts in underground coal mines. It was found that the proposed system was capable of identifying the faulty idlers generating significant heat.
This project benefitted from the collaboration of a group of researchers from The University of Queensland and CRCMining. Tremendous technical guidance and support were also received from ACARP monitors and QBH personnel. During the course of the project, site and laboratory experiments on the proposed monitoring system were designed and carried out. Some of the findings of the early investigations into heat-detection strategies were published in national conference proceedings and received encouraging feedback from mining experts.

The following plan is proposed for the next research project:

- Examination of the system on a full-scale surface conveyor belt to monitor:
  - all rollers
  - driver pulley
  - return idlers
  - other mechanical components.

- Underground trials to examine the system performance for:
  - underground mine environment conditions
  - conveyor belt load variation
  - cable holder surface treatment
  - contamination effects

In order to increase the reliability of the proposed monitoring system, two other fibre optic-based systems (distributed acoustic and vibration sensing systems) will be incorporated and tested in the next stage of the monitoring system design.

**8.2.2 Technology transfer activities**

In the next stage, a technology transfer strategy will be devised that maps the development of the fibre optic-based monitoring system to the point of commercial adoption. The industry will be consulted to review the design features of the sensors to ensure compatibility with the mining environment. Finally, input from the mining industry and original equipment manufacturers will be requested to contribute to the development of a technology transfer
strategy. The project team would like to meet directly with the participants to provide a review of the project outcomes and to seek input regarding the plan to carry out the remaining research activities, before moving to a pilot-scale in-mine implementation and an examination of the technology transfer options.
9 REFERENCES


Bennett, P, 2013. Personal communication, Technical Manager, Sensornet Ltd, 10 May.


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Murace, M, 2012. Personal communication, Sales Manager, Conveyor Belt Monitoring (CBM), 12 December.


Thorpe, P, 2012. Personal communication, Global Diagnostics Manager, Fenner Dunlop Engineered Conveyor Solutions, 8 December.


Appendix I: Risk Assessments

The approach to risk assessment in Australia is based on the AS/NZS 4360:2004: standard for risk management (Australian standard) and the AUSTRAC guidance note Risk management and AML/CTF programs. Risk assessment is required for all operations and experiments involved with hazardous material or equipment. Documentation is compulsory and contributes to reduction of risks by regular reviews. An appropriate risk assessment is expected to recognize possible hazards and outline the actions required to eliminate or reduce any risks linked to an operator’s health.

The following steps are necessary for carrying out a risk assessment:

1. Identification of the hazardous materials, situations, and tasks.
2. Assessment of the likelihood of hazards.
3. Control and reduction of risks by defining procedures and precautions.

The risk matrix is used to categorise the risk level of each hazard. Based on this table, required actions are taken to deal with risks from higher priority to lower priority. Tables A1 and A2, respectively, show the risk matrix and its table of descriptions that are summarized from the mentioned standards.

Table A1: The risk matrix (CRCMining 2011)

<table>
<thead>
<tr>
<th>Likelihood</th>
<th>Likelihood Examples</th>
<th>Risk Rating</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>A</strong> (Almost certain)</td>
<td>Likely that the unwanted event could occur several times per year at this location</td>
<td>15 (M) 10 (H) 6 (H) 2 (Ex) 1 (Ex)</td>
</tr>
<tr>
<td><strong>B</strong> (Likely)</td>
<td>Likely that the unwanted event could occur several times per year in CRCMining; or could happen annually</td>
<td>19 (M) 14 (M) 9 (H) 4 (Ex) 3 (Ex)</td>
</tr>
<tr>
<td><strong>C</strong> (Possible)</td>
<td>The unwanted event could well have occurred in the mining industry at some time in the past 10 years</td>
<td>22 (L) 18 (M) 13 (H) 8 (H) 5 (Ex)</td>
</tr>
<tr>
<td><strong>D</strong> (Unlikely)</td>
<td>The unwanted event has happened in the mining industry at some time; or could happen in 100 years</td>
<td>24 (L) 21 (L) 17 (M) 12 (H) 7 (H)</td>
</tr>
<tr>
<td><strong>E</strong> (Rare)</td>
<td>The unwanted event has never been known to occur in the mining industry; or is highly unlikely that it could ever occur</td>
<td>25 (L) 23 (L) 20 (M) 16 (M) 11 (H)</td>
</tr>
</tbody>
</table>
Table A2: Description of the risk matrix (CRCMining 2011)

<table>
<thead>
<tr>
<th>Risk Matrix Rating</th>
<th>Risk Level</th>
<th>CRCMining Risk Management control guide</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 to 5</td>
<td>(Ex) – Extreme - Immediate correction required - Eliminate, avoid or implement specific plans/ Standards to manage &amp; monitor</td>
<td>Recommend implementation - minimum of 2 hard control Barriers and 2 soft controls</td>
</tr>
<tr>
<td>6 to 13</td>
<td>(H) – High - Should receive attention as soon as possible - Proactively manage</td>
<td>Recommend implementation - minimum of 2 hard control Barriers and 2 soft controls</td>
</tr>
<tr>
<td>14 to 20</td>
<td>(M) – Medium - Should be dealt with as soon as possible but situation is not an emergency - pro actively manage</td>
<td>Recommend implementation - minimum of 1 hard control Barriers and 2 soft controls</td>
</tr>
<tr>
<td>21 to 25</td>
<td>(L) – Low - Risk is normally acceptable - Monitor &amp; manage as appropriate</td>
<td>Monitor and Manage</td>
</tr>
</tbody>
</table>

Table A3: Description of hazard effect and consequences (CRCMining 2011)

<table>
<thead>
<tr>
<th>Hazard Effect/ Consequence</th>
<th>1 Insignificant</th>
<th>2 Minor</th>
<th>3 Moderate</th>
<th>4 Major</th>
<th>5 Catastrophic</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Loss Type</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Harm to People</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(P)</td>
<td>Slight injury or health effects – first aid/ minor medical treatment level</td>
<td>Minor injury or health effects – restricted work or minor lost workday case</td>
<td>Major injury or health effects – major lost workday case/ permanent disability</td>
<td>Permanent total disabilities, single fatality</td>
<td>Multiple fatalities</td>
</tr>
<tr>
<td><strong>Environmental Impact</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(E)</td>
<td>Environmental nuisance</td>
<td>Material environmental harm</td>
<td>Serious environmental harm</td>
<td>Major environmental harm</td>
<td>Extreme environmental harm</td>
</tr>
<tr>
<td><strong>Asset Damage &amp; Other Consequential Losses</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(A)</td>
<td>Slight damage &lt;$5000. No disruption to operation</td>
<td>Minor damage $5000 to $50,000. Brief disruption to operation</td>
<td>Local damage $50,000 to $500,000. Partial shutdown</td>
<td>Major damage $500,000 to $1M. Partial loss of operation</td>
<td>Extreme damage &gt; $1M. Substantial or total loss of operation</td>
</tr>
<tr>
<td><strong>Impact on Reputation</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(R)</td>
<td>Slight impact – public awareness may exist but no public concern</td>
<td>Limited impact – some local public concern</td>
<td>Considerable impact – regional public concern</td>
<td>National impact – national public concern</td>
<td>International impact – international public attention</td>
</tr>
</tbody>
</table>

The following tables (Table A4 and A5) summarises the results of the assessment of the risks associated with laboratory experiments and site trials.
<table>
<thead>
<tr>
<th>Work area / Task Activity</th>
<th>Potential Hazard</th>
<th>Existing controls</th>
<th>Loss Type</th>
<th>Likelihood</th>
<th>Risk Score</th>
<th>Risk</th>
<th>Additional Controls</th>
</tr>
</thead>
<tbody>
<tr>
<td>Move DTS unit into place</td>
<td>Manual handling</td>
<td>Unit has wheels</td>
<td>P</td>
<td>D</td>
<td>17</td>
<td>Medium</td>
<td>Add the existing controls to job instruction</td>
</tr>
<tr>
<td>Configure Conveyor test stand</td>
<td>Idler Frame can topple over crushing foot</td>
<td></td>
<td>P</td>
<td>C</td>
<td>13</td>
<td>High</td>
<td>Make frame more stable, safety footwear (see below)</td>
</tr>
<tr>
<td>Insert idler into test stand</td>
<td>Dropping idler on foot</td>
<td></td>
<td>P</td>
<td>C</td>
<td>13</td>
<td>High</td>
<td>Add to JI Safety Frame to be worn at all times and signage. Safety footwear unless supervised</td>
</tr>
<tr>
<td>Insert heat source</td>
<td>Cutting hands or pinch points handling idler</td>
<td></td>
<td>P</td>
<td>C</td>
<td>18</td>
<td>Medium</td>
<td>Wear leather gloves at all times when handling idler</td>
</tr>
<tr>
<td>Set up power supply for heating element</td>
<td>Trip Hazard from cables on ground</td>
<td></td>
<td>P</td>
<td>C</td>
<td>13</td>
<td>High</td>
<td>Re-route cabling to non-trafficked areas of lab</td>
</tr>
<tr>
<td>Connect fibre cable</td>
<td>Hazard of fibre optic laser source - LASER source weak</td>
<td>Reviewed the manufacturer’s safety manual, identified the controls that are required by the manufacturer, having an information sign on the equipment not to look directly - Laser source is weak</td>
<td>P</td>
<td>D</td>
<td>11 Low</td>
<td>Low</td>
<td>Wear dust mask when conducting dusty activities and clean the lab to remove dust</td>
</tr>
<tr>
<td>Clean laboratory</td>
<td>Coal dust</td>
<td>The room is not clean but does not contain any volume of dust that can be considered unsafe creating an unhealthy environment</td>
<td>P</td>
<td>D</td>
<td>17 Medium</td>
<td>Medium</td>
<td>Wear dust mask when conducting dusty activities and clean the lab to remove dust</td>
</tr>
<tr>
<td>Using Electrical Equipment</td>
<td>Electricity from 240V equipment</td>
<td>All equipment and circuitry is tested and tagged and in date, including extension cords</td>
<td>P</td>
<td>C</td>
<td>8</td>
<td>High</td>
<td>All equipment and circuitry is tested and tagged and in date, including extension cords</td>
</tr>
<tr>
<td>Unused Heat Lamp in the Lab</td>
<td>Burn or Fire</td>
<td></td>
<td>P</td>
<td>C</td>
<td>13</td>
<td>High</td>
<td>Apply out of service tag to heat sources that are stored in lab but not used. Tag must say that a risk assessment is required before use</td>
</tr>
<tr>
<td>Hot Water Tap</td>
<td>Hot water may be so hot that a building may melt</td>
<td></td>
<td>P</td>
<td>C</td>
<td>18</td>
<td>Medium</td>
<td>Measure water temperature, investigate burn threshold temperature. Add signage and PPE stored at that location - PVC gloves</td>
</tr>
<tr>
<td>Electrical GPO’s</td>
<td>Electrical equipment may result in electrocution</td>
<td></td>
<td>P</td>
<td>D</td>
<td>12</td>
<td>High</td>
<td>Add information tag to heat sources and use barriers. Tag must say do not touch apparatus</td>
</tr>
<tr>
<td>Unattended hot roller in lab</td>
<td>A passer by burns themselves on roller</td>
<td></td>
<td>P</td>
<td>C</td>
<td>13</td>
<td>High</td>
<td>Apply information tag to heat sources and use barriers. Tag must say do not touch apparatus</td>
</tr>
<tr>
<td>Old and unknown gas supply piping</td>
<td>A fire occurs when lab is unattended</td>
<td></td>
<td>A</td>
<td>C</td>
<td>13</td>
<td>High</td>
<td>Like to be more than one metre from wall of lab. Place oil catch tray under apparatus</td>
</tr>
<tr>
<td>Old gas bottle in lab</td>
<td>Pipe leaks</td>
<td></td>
<td>P</td>
<td>C</td>
<td>13</td>
<td>High</td>
<td>Identify the type of the piping contents, isolatethe pipes outside of lab and tag with out of service tag</td>
</tr>
<tr>
<td>Old lino tiles pooling</td>
<td>Floor surface peeling presents a trip hazard</td>
<td></td>
<td>P</td>
<td>C</td>
<td>13</td>
<td>High</td>
<td>The tiles in the lab are the same as the tiles in the whole building, according to the building manager, Aaron Baxter, the tiles are safe as long as we do not grind or drill into the tiles.</td>
</tr>
<tr>
<td>Air -Con Unit is dirty</td>
<td>Dust and maybe hazardous fibre</td>
<td></td>
<td>P</td>
<td>C</td>
<td>13</td>
<td>High</td>
<td>The air conditioning unit has been cleaned and serviced.</td>
</tr>
<tr>
<td>Cutting activities</td>
<td>Lacerations</td>
<td></td>
<td>P</td>
<td>C</td>
<td>18</td>
<td>Medium</td>
<td>Scissors and shears- Use PPE (gloves)</td>
</tr>
<tr>
<td>Visitors in lab</td>
<td>Injury</td>
<td></td>
<td>P</td>
<td>C</td>
<td>13</td>
<td>High</td>
<td>Better tape to separate visitors from idlers and compulsory visitors solution</td>
</tr>
</tbody>
</table>
### Table A4: Risk assessment for site trials

<table>
<thead>
<tr>
<th>Work area / Task Activity</th>
<th>Potential Hazard</th>
<th>Existing controls</th>
<th>Loss Type</th>
<th>Likelihood</th>
<th>Consequence</th>
<th>Risk Score</th>
<th>Risk</th>
<th>Additional Controls</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Trip/Fall while installing the fibre optic cable</td>
<td>Ensure the cable is not in the walkway and secure the cable to the rails, Follow 3 points of contact - Site has stable platform and handrails that prevents falling from height</td>
<td>P</td>
<td>3</td>
<td>D</td>
<td>17</td>
<td>Medium</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Cutting hands or pinch fingers while installing the Cable Holders</td>
<td>Wear leather gloves and use appropriate tool.</td>
<td>P</td>
<td>2</td>
<td>D</td>
<td>21</td>
<td>Low</td>
<td>Use appropriate tool such as side cutters</td>
</tr>
<tr>
<td>Tests with stationary belt</td>
<td>Cutting hands or pinch fingers/ Dropping idler on foot while Replacing the idler</td>
<td>Wear leather gloves and safety boots, This procedure should be carried out by an experienced worker</td>
<td>P</td>
<td>2</td>
<td>D</td>
<td>21</td>
<td>Low</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Dropping objects such as Idler, coal particles, tools etc from the working area to the levels below</td>
<td>Informed the working area to the site supervisor, Wear safety clothing including helmet</td>
<td>P</td>
<td>4</td>
<td>C</td>
<td>8</td>
<td>High</td>
<td>Isolate the working area from people entering and attach information tag to barriers informing workers to be aware of overhead hazards</td>
</tr>
<tr>
<td></td>
<td>Burning hands on glow plug or high temperature while inserting the heat source in the roller</td>
<td>Wear leather gloves, control glow plug temperature by voltage transformer</td>
<td>P</td>
<td>3</td>
<td>D</td>
<td>17</td>
<td>Medium</td>
<td>Only insert the heat source when it is isolated</td>
</tr>
<tr>
<td></td>
<td>Sudden motion of the conveyor belt</td>
<td>Use personal isolation lock before and while working on the belt</td>
<td>P</td>
<td>4</td>
<td>E</td>
<td>16</td>
<td>Medium</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Hazard of fibre optic laser sources in the DTS units</td>
<td>Reviewed the manufacturers safety manual, Identified the controls that are required by the manufacturer, Having an information sign on the equipment, Not to look directly to the laser - Laser source is weak - Class 1M - Inserting the E2000 connectors to DTS has no risk.</td>
<td>P</td>
<td>2</td>
<td>D</td>
<td>21</td>
<td>Low</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Damage the fibre</td>
<td>Experienced person makes the connections</td>
<td>A</td>
<td>2</td>
<td>D</td>
<td>21</td>
<td>Low</td>
<td></td>
</tr>
<tr>
<td>Additional activities with the operating belt</td>
<td>Hurt by dynamic force while the conveyor belt is running</td>
<td>Use barrier tape to isolate the section of the belt where the idler guards have been removed. Attach the Information Tag: “No entry testing is in progress-conveyor is running without idler guards”</td>
<td>P</td>
<td>4</td>
<td>D</td>
<td>12</td>
<td>High</td>
<td>Do not enter barriered area unless the power to the belt has been isolated and locked with a personal lock.</td>
</tr>
<tr>
<td></td>
<td>Electrical or Fibre-optic Cables get caught with the operating belt</td>
<td>Check the cable and holders to be in safe place away from the belt before starting the belt, Isolate the section of the belt where the cables are installed, Do not make any changes to the experimental setup while conveyor belt is running</td>
<td>A</td>
<td>3</td>
<td>D</td>
<td>17</td>
<td>Medium</td>
<td></td>
</tr>
</tbody>
</table>
Appendix II: Certificates of Merit Awarded

Faculty of Engineering, Architecture and Information Technology
Postgraduate Research Conference 2014

The Faculty is pleased to congratulate:

Ben Yang

The Professor Don Nicklin Prize
Best Presentation Relating to Mining Engineering

[Signature]
Professor Simon Biggs
Executive Dean
Faculty of Engineering, Architecture and Information Technology
June 2014

THE UNIVERSITY OF QUEENSLAND
AUSTRALIA