Coal Operators' Conference

Faculty of Engineering and Information Sciences

2012

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Jonathon C. Ralston
CSIRO, Queensland

Andrew D. Strange

Publication Details

J.C. Ralston and A.D. Strange, Thermal infrared-based seam tracking for intelligent longwall shearer horizon control, 12th Coal Operators' Conference, University of Wollongong & the Australasian Institute of Mining and Metallurgy, 2012, 78-85.

THERMAL INFRARED-BASED SEAM TRACKING FOR INTELLIGENT LONGWALL SHEARER HORIZON CONTROL

Jonathon C Ralston and Andrew D Strange

ABSRACT: Longwall mining remains one of the most efficient methods for underground coal recovery. A key aspect in achieving safe and productive longwall operations relies on maintaining the shearer in an optimal position for extraction within the coal seam. The typical approach to this resource identification issue is labour intensive so is subject to safety and productivity drawbacks. As a solution, this paper describes the use of thermal infrared-based sensing to provide a means to automatically measure the vertical position of the mining machine with respect to the coal seam. This is achieved by identifying and tracking non-optically visible horizontal line-like bands in the main body of coal, which are known as marker bands. These marker bands are strongly linked to the profile of coal seam structure, a geological characteristic often used by operators as an ad hoc datum for maintaining in-seam alignment of the shearer. Details on the theory behind thermal infrared imaging and practical aspects involved in implementation of the method are given. As there are very few real-time solutions available to locate and track coal seam profiles, this approach overcomes a current limitation in implementing intelligent horizon control systems for advanced shearer operation. Measurements from a shearer-based sensing system are given to demonstrate the approach.

INTRODUCTION

Longwall mining

Longwall coal mining is a full extraction underground mining method that involves the removal of coal in large blocks or panels using a mechanised shearer. The coal panel is typically 200-350 m wide and can be up to five kilometres in length. The mechanical shearer is mounted on a shearer pan and rails which guide the shearer as it moves back and forth across the coal face. With this method of mining, the roof is supported by hydraulic shields that are individually advanced as mining progresses. As the roof support system advances into the coal panel, the mine roof is allowed to collapse into the void behind the shields. For reference, a representation of a small portion of a longwall operation and shearer is shown in Figure 1. The coal seam is indicated by the hatched layer between the underlying and overlying strata.

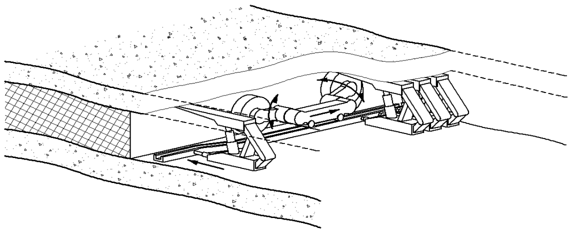

Figure 1 - Representation of a small portion of a longwall operation. The coal seam is indicated by the hatched layer between the underlying and overlying strata. For clarity, the central section of the roof support system is not shown.

LASC automation

Over the past decade, the CSIRO Mining Technology Research Group has undertaken focussed research and development activities to deliver a means to accurately determine both the location and orientation of the shearer in real-time. This technical innovation developed a new automated face alignment capability and new options for extraction control, allowing the shearer to accurately achieve a given path and geodetic heading (Reid, *et al*., 2006). The benefits of this outcome have been broadly recognised and embraced by the longwall community and have subsequently been taken through to

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[1] *Email: Jonathon.Ralston@csiro.au*

commercial maturity through an industry-driven Longwall Automation Steering Committee (LASC, 2011).

The need for coal resource location

However, achieving a highly productive longwall operation relies not only on accurately knowing the location of the equipment but also on precise information regarding the spatial location of the coal resource. This information is critical in order to maintain the shearer in an optimal position for extraction within the coal seam. Operating in seam is also important in terms of minimising damage to equipment, reducing dust production, and to relieve personnel from potential hazards such as hard-rock debris dislodged from out-of-seam mining. In an attempt to provide a solution to this problem, this paper considers the use of machine-based sensing, specifically a Thermal Infrared Camera (TIR), to provide a means to measure the vertical position of the shearer with respect to the coal seam. The processed sensor output can then be applied to any LASC compliant longwall automation system to provide geologically intelligent information for real-time shearer horizon control.

SEAM TRACKING BY MARKER BANDS

The importance of marker bands

The standard approach for identifying coal seam boundaries requires shearer operators to monitor various indicators such as visual cues present in the geology, a change in dust conditions when transitioning coal-rock boundaries, or inspection of the extracted resource. For a variety of reasons the most efficacious methods are based on observing the geological characteristics associated with the overall coal seam.

The material mined during the longwall operation is composed several layers of coal, clay or ash of varying thicknesses. This horizontal layering characteristic is well known in underground coal operations, where the overall body of coal to be extracted also contains thin horizontal layers or bands which consist of high ash-content material. These thin horizontal layers are often referred to as marker or penny bands, which visibly contrast with the host coal strata because of their light-grey or white colour. The nature and presence of marker bands is geology-dependent, so that they may or may not be observable to the naked eye in a given longwall operation. Figure 2 shows a short section of a longwall face revealing the characteristic horizontal geology of coal and marker bands.

Manual tracking of marker bands

In terms of shearer guidance, the major interest in marker bands arises because the bands often exhibit similar horizontal trends to the host coal seam geology. For operators, marker bands are particularly important as they often provide the only visible indicator to infer the relative vertical location of the shearer with respect to the overall geological coal seam trend. To maintain the shearer in a desired coal seam horizon, an operator will manually note the vertical distance of a particular marker band from the floor (or roof) extraction boundary at a nominal location across the face, and then attempt to hold that distance constant as the shearer progresses across the face. In order to achieve reliable and effective horizon control, this process needs to be maintained in a similar fashion as the shearer retreats into the panel.

Figure 2 - Photo taken of an underground longwall face which shows characteristic darker coal and lighter marker band features. A dominant marker band is seen at the bottom of the image, as well as finer, less immediately obvious bands above. The top of the image shows sections of the roof canopy support.

Limitations to manual band tracking

The manual approach for shearer horizon control has obvious drawbacks, particularly in terms of the amount of human effort necessary to constantly identify and track the geological marker band features in light of other operational duties. Being a manual process, there remains a practical requirement to both record and relay information across shearer crews regarding the state of horizon tracking.

Practical situations also arise where the marker bands are simply not observable due to the dust generated from extraction, equipment temporarily restrict the field of view, and operational duties and hazards effectively prohibiting ready access to observe the face. These practical issues in turn affect the quality and consistency of the overall coal recovery process, and ultimately serve to impact on production performance.

Automatic sensing of marker bands

Many of the challenges associated with manual band tracking, however, could be overcome if a reliable means of sensing could be developed to automatically generate a vertical datum for horizon control. Presently, very few (if any) reliable real-time solutions exist to locate and track seam profiles. To this end, research and development was undertaken in an attempt to provide solutions to this problem.

Marker band tracking using vision-based sensing

Initial research concentrated on replicating human vision capability using a visible-light camera. This produced imagery as seen in Figure 2, where a camera was installed on a supporting chock. A prototype system was developed consisting of three camera units. To minimise cable runs, the camera system also trialled a Broadband over Power Line (BoPL) technology and where Ethernet-based communications were maintained via the 110VAC supply. Figure 3 shows the visible light camera system being evaluated during in-house validation.

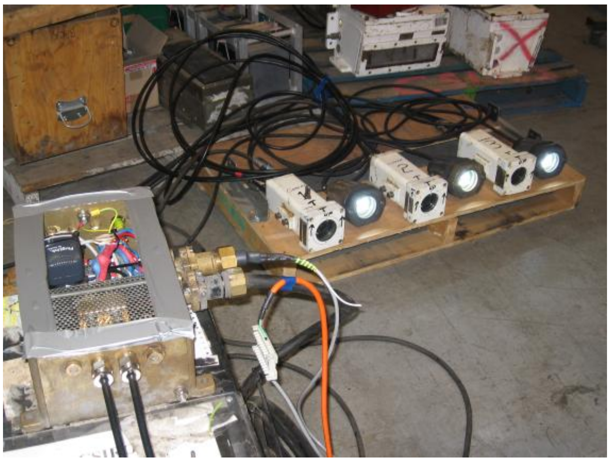

Figure 3 - In-house validation of a three-camera visible light camera system. To the left of the image is the junction box which houses the communications components, and to the right are the cameras and lighting flameproof enclosures.

The visible-light camera method represented an intuitive approach to marker band tracking that yielded some useful outcomes. However, the particular implementation also gave rise to some interesting limitations in practice, particularly in terms of its application to the shearer horizon control problem. Four specific limitations encountered were:

- The requirement for near constant illumination in order to clearly image the longwall face;
- The presence of water and dust, which often completely blocked any visible- light imaging;
- A single, fixed position for sensing restricted observability to a small portion of the face;
- Some minesite geology simply did not give rise to readily observable visible marker bands.

Marker band tracking using thermal infrared sensing

To overcome the limitations associated with a visible-light camera configuration, an alternative approach was considered that utilised TIR sensing. The idea of using TIR imaging is based on the concept that all objects emit thermal infrared energy based on their temperature. This energy can be detected using a device that is sensitive to radiation in the thermal infrared range of the electromagnetic spectrum. TIR energy is not visible to the human eye, but rather operates at a different region of the electromagnetic spectrum as noted in Figure 4.

The specific linkage between TIR sensing and longwall operations becomes apparent by noting that the engagement of the rotating shearer drum with the coal face surface gives rise to regions of thermal contrast due to frictional interaction. These temperature differences are observable in the thermal-infrared region of the electromagnetic spectrum. The intensity of this radiation can be detected by an infrared camera and displayed as a digital image, where the pixel values represent the measured TIR intensity.

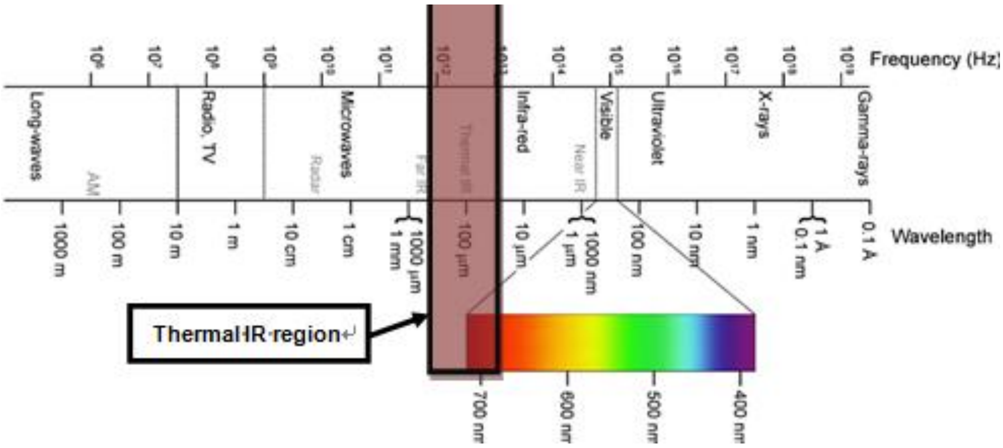

Figure 4 - The full electromagnetic spectrum, showing the wavelengths associated with thermal infrared energy. For comparison, the familiar visible light spectrum is also shown. (Courtesy L. Keiner, Coastal Carolina University, adapted).

Thermal infrared cameras

A typical output of a camera is represented as a grey-scale image of varying pixel intensity values where darker and lighter respectively correspond to cooler and hotter objects. A thermal infrared camera can produce live images, much like a video camera, but based on temperature variation in the field of view. Most thermal cameras operate in the low to mid thermal range of the electromagnetic spectrum, being sensitive to electromagnetic energy with wavelengths in the range of 1 - 15 µm. Figure 5 shows a typical compact thermal infrared camera, which is ideal for housing in small flameproof enclosures with a window transparent to TIR radiation (FLIR 2010).

Figure 5 - A typical compact TIR imaging camera for OEM use (Omega, now FLIR). The small-form factor means that it can be readily incorporated into existing approved flameproof enclosures.

Advantages of thermal imaging over vision

TIR technical offers several advantages over traditional vision-based imaging for the shearer guidance problem. In particular, the technology has important operational characteristics which can overcome the limitations associated with vision-based sensing:

- TIR cameras can operate in complete darkness without any loss of image quality, i.e., the camera output is independent of the level of ambient (visible) light present;
- It can effectively penetrate through large dust and water particles, allowing imaging in a much broader range of operational conditions than possible with visible light cameras;
- Thermal cameras are similarly sized to regular vision cameras, and so can be conveniently deployed in a mining context where mounting space is limited, e.g. a mobile shearer-based installation;
- Sensing of novel "thermal marker bands", which are thermally observable features strongly linked to visible marker bands and thus coal seam trends, but which are otherwise invisible to the human eye.

Flameproof enclosure

A practical system for underground use must be installed in a flameproof enclosure that can accommodate the unique characteristics of a TIR camera (Ralston, *et al.,* 2006). The flameproof enclosure must also meet the constraints of IEC Ex d standards, namely impact testing, chemical inertness, and pressure testing. However, unlike regular vision-based imaging, thermal-infrared energy cannot readily penetrate through the standard glass or Perspex window typically used for flameproof enclosures. It is therefore necessary to utilise a material that supports transmission of TIR radiation. Of all the candidate materials possibly for this, a germanium-based window is most favourable, and hence a compliant enclosure utilising this material was developed (see Figure 6).

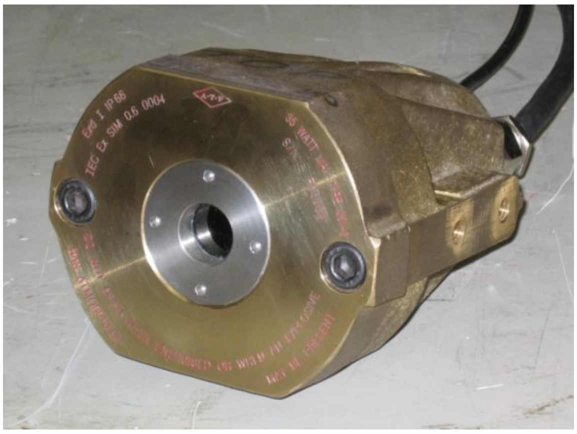

Figure 6 - An approved TIR thermal infrared flameproof enclosure and camera conforming to IEC Ex d standards

Thermal infrared camera mounting location

An ideal location for the thermal infrared camera is on the body of the mining machine, oriented such that it has a useful viewable aspect of the drum and surrounding strata while itself being sufficiently protected from the rough operational conditions.

Figure 7 shows output from a thermal infrared camera mounted on the body of the shearer that provides a view of the face and cutter drum activity, conducted as part of the original Landmark Longwall Automation activity (Kelly, *et al*., 2006). This image shows temperature variations on both the face and roof which correspond to different areas of thermal intensity. Figure 7 also shows additional detail in the thermal domain associated with the interaction of the cutter drum with the roof. As the cutting drum departs from the (relatively soft) coal seam and encounters harder shale or rock material, an increase in frictional forces occurs which leads to an increase in temperature of the cutting picks and the surface where material is being extracted. This increase in temperature is readily observable in the TIR thermal infra-red domain, appearing as a noticeable increase in image intensity in the vicinity of the cutting drum (see top of Figure 7). This additional information from the seam boundary can be processed in a similar manner to the marker-band detection process to provide a coal-interface detector to localise the upper and (with a second TIR camera) lower boundaries of the coal seam.

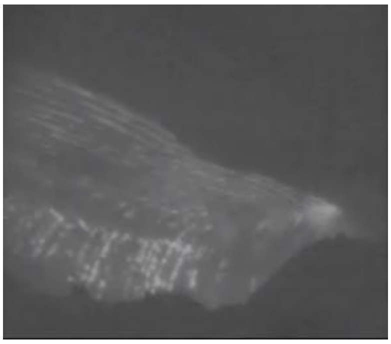

Figure 7 - Thermal image acquired from a shearer-mounted TIR thermal infrared camera. The viewing region has the camera directed upwards towards the longwall face and roof, with the cutting drum to the right. Thermal regions are mapped to image intensity: lighter sections correspond to higher temperatures and darker sections to lower temperatures.

IMAGE PROCESSING AND SEAM TRACKING

Thermal image acquisition

Figure 8 shows a typical snapshot of the thermal imaging camera video stream acquired from the camera mounted on the shearer towing arm at a longwall mine. This image shows a horizontal feature, corresponding to a "thermal marker band", arising from the frictional forces acting on material with harder mechanical properties. It should be noted that this thermal feature is not visible to the human eye. The darker section on the bottom third of the image is coal build up on the shearer body.

Of note, this image was acquired in geological conditions where the shearer produced a large amount of airborne particles and debris; hence the face was almost unobservable for visible-light systems. However using TIR imaging the band feature is still readily apparent, demonstrating a key property of TIR thermal infrared imaging technology: its imaging quality is not as severely degraded by particulate matter as an ordinary video camera.

Figure 8 - Typical thermal infrared image acquired from the camera mounted on the shearer towing arm at Broadmeadow longwall. At the top of the image are the roof supports, mid section shows a TIR thermal infrared feature, and at the base is the shearer body.

Data processing

Preliminary data processing was performed on the TIR images in order to evaluate the potential of a line-based tracking algorithm for horizon datum generation. The results of this processing are shown in Figures 9 and 10. The left figure of Figure 9 shows the original TIR image and the right image shows the superimposition of automatically extracted line segments corresponding to the thermal marker band.

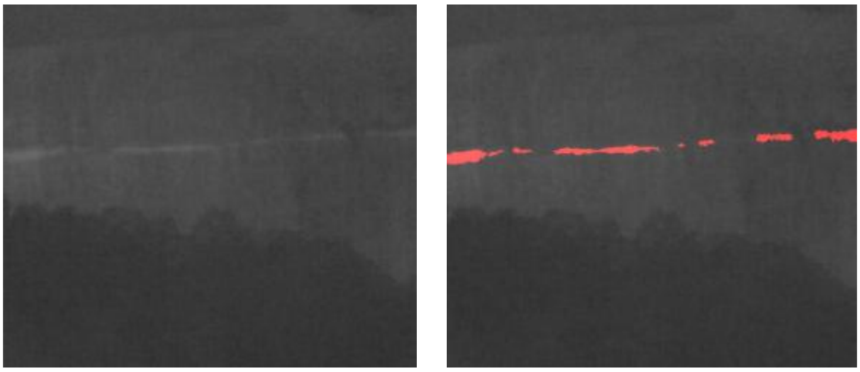

Figure 9 - Original thermal image (left), and tracked thermal marker band (right)

Figure 10 shows the extracted marker band position information in a form that is useful for horizon datum generation. Note that a simple interpolation is performed in sections where the tracked marker-band quality is degraded (see Figure 9). This demonstrates how the TIR image data can be meaningfully used for the development of an online automated horizon sensing capability.

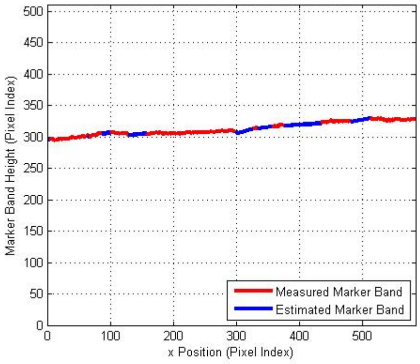

Figure 10 - Automated horizon datum extraction from a single thermal infrared TIR image acquired from the Broadmeadow longwall thermal infrared trial

LASC compliant system integration

The information generated from the TIR sensor can be integrated with an existing LASC longwall cut-model database to provide a horizon control system. This involves LASC-compliant communications, intelligent processing, system validation and integration. Underground longwall personnel will control and manage the system through an updated graphic user interface that is incorporated into the LASC-standard Operator Controller Display (OCD). This allows the operator to set the desired horizon extraction according to a pre-determined strategy. It will also provide a graphical display of the desired extraction profile and the option to either select or ignore this input. The block diagram in Figure 11 shows the overall system topology to integrate the TIR based sensing into an existing Longwall configuration.

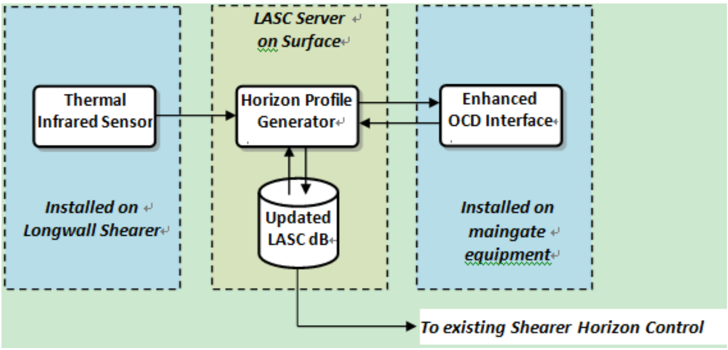

Figure 11 - Interconnection of TIR based sensor with an existing LASC compliant system

DISCUSSION

The evaluation of the TIR camera has identified it as a very useful tool for developing an automated horizon steering capability. These results serve to consolidate existing thermal infrared data acquired in a previous thermal imaging trial at Beltana. Of special note, different geological conditions in the later study at Broadmeadow led to the generation of new and highly useful techniques for processing thermal features.

Amongst other lessons learnt from the later trial, it was clear that the location of the thermal imaging camera and its mounting angle plays an important role in the performance of band feature detection. The results suggest that the camera should be mounted perpendicular to the face to provide the most robust thermal features for automated marker band detection.

Further investigation needs to be undertaken to determine a means to allow for the longer term implementation of the shearer-based camera deployment. Practical survivability of the enclosure is an ongoing challenge, but several options have been considered and it is believed that a viable solution is possible.

Possibilities also exist to utilise a number of cameras at fixed locations, e.g., mounted on the roof supports rather than a single camera on a mobile shearer. Several useful developments can be made using the TIR imaging system to provide additional monitoring capability. In particular, thermal disparity associated with voids in the face could form the basis of an automated face integrity monitoring system.

SUMMARY

This paper described developments associated with thermal infrared imaging to provide a means to measure the vertical position of the mining machine with respect to the coal seam. Both optical and thermal approaches were presented as a means to identify and track marker band features towards providing an automated sensing strategy for shearer horizon control. A LASC-compliant integration of such a system was also described. Developments in this area are important for realising intelligent shearer horizon control systems that will boost productivity and enhance safety for operators.

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