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Multi-sensor data fusion for the detection of underground coal fires

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Abstract

The spontaneous combustion of coal causes widespread underground coal fires in several countries, amongst which is China. These coal fires cause serious environmental, economic and safety problems. In northern China, the coal fires occur within a wide region stretching 5000 km east-west and 750 km north-south. Remote sensing therefore provides an ideal tool for monitoring this environmental hazard over such a large and remote area. As part of a research project to detect, measure, monitor and extinguish these coal fires, this paper describes a remote-sensing-based multi-sensor data-fusion methodology for detecting the underground fires. The methodology is based on fusing a variety of satellite-based image types (optical, thermal, microwave) together with airborne data (optical and thermal infrared) and ancillary data sources such as geological and topographic maps. The results of the remote-sensing data fusion are presented, using pixel-based, feature-based and decision-based fusion approaches.

Introduction

The spontaneous combustion of coal is a common problem in many coalfields throughout the world. Those in the United States, Australia and India have been extensively studied (Fischer & Knuth 1968, Ellyett & Fleming 1974, Prakash et al. 1995). However, these coal fires almost fade into insignificance compared to the size, extent, and amount of coal lost by coal fires in northern China. Here, remote-sensing satellite-data studies have shown that coal fires occur from northwest to northeast China in a belt stretching 5000 km in east-west and 750 km in north-south direction (Guan 1984, 1989). Figure 1 shows a location map, indicating the main coal fields where underground coal fires occur. The annual losses are estimated at 100 million tons of coal (Rozema et al. 1993). In 1987, the ITC was invited by the Chinese Ministry of Coal Industry to study this problem using remote-sensing techniques. For the past ten years, researchers from ITC and the Chinese partners have studied the use of almost all satellite-derived data types, as well as various airborne techniques to detect, measure and monitor the underground coal fires in numerous regions of northwest China. These have included the provinces of Shanxi, Gansu and Shaanxi, and the autonomous regions of Inner Mongolia, Ningxia and Xinjiang (Zhang et al. 1995, Cassells & Van Genderen 1995, Cassells et al. 1996, Van Genderen et al. 1996).

What these studies, and the majority of the published literature on the detection of underground coal fires show, is that several satellite and airborne sensors can partially detect such fires, depending on certain conditions such as size of the fire, depth of the fire, relief, time of the data acquisition, prevailing weather conditions, time of the year, etc.

Realizing that each sensor and its associated image-data type only provides part of the detection of the coal fires, the objectives of the research described in this paper are to fuse the data, feature or information extracted from each individual sensor source in order to have a more complete, robust and reliable

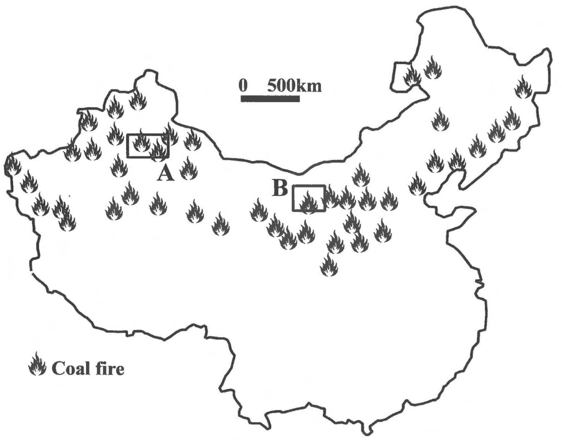

Figure 1. Location map showing distribution of underground coal fires in northern China. The two boxes marked A, the Xinjiang Weiwuer Autonomous Region, and B, the Ningxia Hui Autonomous Region, are the two detailed test areas for checking the multi-sensor data sets described in this paper.

result on the location of the coal fires. For example, in optical imagery, the burnt rock above the coal fire often displays a unique spectral signature as the baked rocks have a different reflectance than the natural overburden. However, optical imagery does not indicate whether the burnt rock is caused by a fire that is presently active or by paleo-coal-fires that are known to have occurred in the area due to spontaneous combustion since Pleistocene time (Zhang 1998). Similarly, thermal infrared data from satellites can identify hot spots which could be underground coal fires only under certain conditions. Hence, the methodology of the multi-sensor data fusion in this paper suggests that by using multiple sensors simultaneously, more reliable data will result in the location of the coal fires than would be possible by using them independently.

Geological setting

For this research, three relatively well accessible areas, namely Toutunhe, Xishan and Sangong-Dahuangshan were selected. These are located on the northern side of the Tianshan mountains, close to Urumqi, the capital city of Xinjiang Weuwer Autonomous Region, northwest China (Figure 1). The test areas are in a semi-arid zone with very sparse vegetation coverage, crossed by several rivers. The coal-bearing strata are located at an altitude between 800 and 1400 m in the transition zone of the east-west trending Tianshan Mountain foldbelt and the Junggar basin to the north. The core of the Tianshan Mountain range consists of pre-Mesozoic basement rocks with on the northern side Mesozoic and Cenozoic sedimentary rocks that have been folded in east-west direction at the end of the Cretaceous. The southernmost folds incorporate the coal-bearing Jurassic rocks. The main coal-bearing strata that have burnt out belong to the Lower Jurassic Badaowan Group and the Middle Jurassic Xishanyao Group. These groups consist of fresh-water deltaic sediments including mudstone, siltstone, sandstone and coal layers (Schneider 1996). Between two and eleven layers are considered mineable depending on the location. The coal layers are concentrated in the lower parts of the Xishanyao Group and Badaowan Group and have thicknesses varying from 1 to 27 m. The coal-bearing strata have been incised by northward flowing rivers and their tributaries (Molnar et al. 1994). Within these areas, active coal fires as well as burnt rocks, of which most are the result of Pleistocene coal fires, are widespread (Zhang 1998). The underground fires originally start due to spontaneous combustion at the outcrops and then spread deeper into the coal seams. The coal fires also begin in underground coal mines and spread upwards. As a result, the overburden rocks are thermally metamorphosed and the heat from the fires causes iron in the sediments to oxidise, therewith changing the colour of the rocks from grey to red.

Field research was carried out in Xinjiang from 21 September to 1 November 1994, and from 6 August to 18 September 1995. The surface temperature of the coal fires was measured using a Japanese-made portable pyroelectric infrared thermal radiometer. This provided ground truth data for the remote-sensing interpretation. Field data was gathered and reflectance spectra were measured to improve the understanding of other aspects of the coal fires.

Detection of underground coal fires

Underground coal fires can cause a series of changes at the land surface. These include: an increase in temperature, emission of smoke, colour changes of caprock, formation and deposition of new materials at the surface (e.g. sulphur, salmiac deposits), and land cracking and subsidence. These changes at the surface are used by the various remote-sensing platforms and sensors as indicators of sub-surface fires.

Smoke and thermal anomalies are considered to be direct indicators as they can be seen clearly and

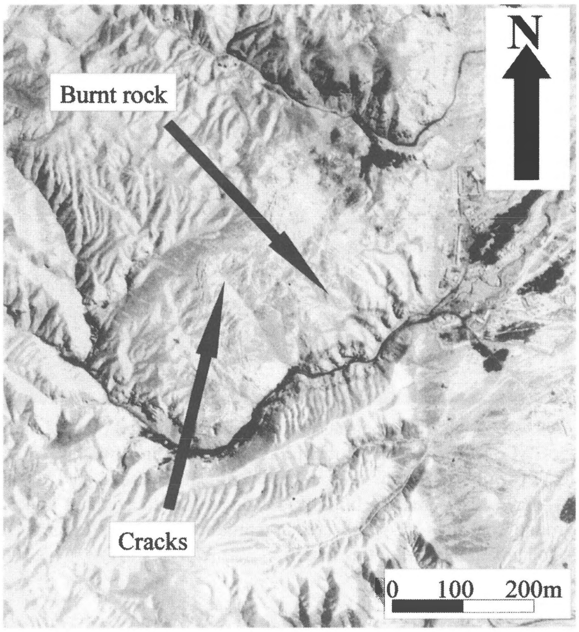

Figure 2. Extract from a colour infrared aerial photograph of an underground coal-fire area near Liuzhuangzi, taken 7 August 1992. Note the distinctive yellowish orange colour of the burnt rock. Immediately adjacent to the central area of burnt rock, an extensive area of land subsidence is indicated by the long, parallel cracks in the land surface. (For full colour reproduction of this figure, see Appendix at the end of this issue.)

directly on air photos and thermal infrared imagery respectively. Short-wave infrared can also detect coal fires directly if the thermal anomalies caused by the fire have a temperature higher than 160 °C (Zhang 1998).

The other indicators cited above, such as spectral reflectance changes in the caprock, land subsidence etc., are referred to as indirect indicators of such subsurface coal fires because these characteristics cannot, by themselves, indicate whether an underground coal fire is still burning or not (Zhang 1998). The following paragraphs provide the results of single-sensor detection techniques to find underground coal fires. This will be followed by a description of the newly developed multi-sensor data-fusion approach, together with a discussion of the results and benefits.

Aerial photography

Aerial photography has been found to be very useful for studying underground coal fires. Colour-infrared aerial photographs, an example of which is here reproduced as Figure 2, show cracking and land subsidence. Together with the unique spectral reflectance of the burnt caprock, these features indicate the presence of an underground coal fire. In particular, stereoscopic 3-D study of the aerial photographs can provide detailed information on the geological configuration.

The limitations of aerial photography lie in the high cost to acquire regional coverage on a regular basis for monitoring purposes, certainly when an area of 5000 × 750 km is involved. The huge number of aerial photographs that would need to be interpreted is another drawback.

Airborne thermal infrared data

This well-established technique has been used to detect underground coal fires since 1963. Slavecki (1964) used it to detect coal fires in Pennsylvania, U.S.A. Since then it has been used successfully to detect and measure sub-surface coal fires in many countries (Greene & Moxham 1969, Guan 1989, Bhattacharya & Reddy 1994, Zhang et al. 1995). Day-time data is often acquired in both the thermal-infrared windows of 3 to 5 μm and 8 to 14 μm. Typically, the best results are obtained during a pre-dawn flight when thermal contrasts between the fire areas and the colder non-fire areas are strongest. The technique has also been used to detect the depth and direction of coal fires underground (Saraf et al. 1995, Cassells & Van Genderen 1995).

Digital cameras and imaging devices operating in the thermal region generally use two black bodies of known temperatures (one of high and one of relatively low temperature) to calibrate the sensor-received signal directly to temperature using a linear regression of the observed read-out and the black-body temperature. With digital thermal infrared data it is important to set the two internal black-body reference temperatures at realistic figures with respect to the expected temperature ranges on the ground. It should be noted that anomalies due to coal fires generally exceed by far the normal ground-temperature fluctuations due to solar heating. A lower, and a higher reference temperature are given to the two internal black bodies in the thermal infrared scanner. These are then related to digital values ranging from 0 to 255. Any temperature above that of the higher black-body reference temperature will be saturated, that means that we cannot infer temperatures for objects of which the temperature exceeds that of the warmest black body. Coal fires typically produce signals that exceed by far the range of common black-body temperatures. This means that no quantitative temperature analysis can be done, although for simple detection this is not a problem.

In terms of large area coverage and costs, the same drawbacks apply as for aerial-photography. Hence in practice, these airborne techniques are mainly used for detailed studies of known coal-fire areas which have been found by either satellite-based or field-based methods.

High-resolution optical satellite data

Earth observation satellite imagery derived from Landsat TM, SPOT and SOYUS satellites has been used to study coal-fire areas. The six optical bands of Landsat TM with 30 m resolution can, with suitable processing techniques, enhance the data to highlight the major areas of burnt caprock. The synoptic overview provided by an image (180 × 180 km) also greatly aides in studying the coal fields in their regional settings. SPOT XS (three bands) at 20 m spatial resolution has shown to be less useful than TM, both in terms of area covered (only one tenth that of Landsat TM) and in the choice of spectral bands. SPOT Pan (10 m spatial resolution), especially in stereomode, is a useful tool because it combines both spectral information with the height information allowing a three-dimensional perspective of the ground to be inferred. In addition, a Digital Elevation Model (DEM) can be produced from its data, which is especially helpful in areas where no detailed maps are available. The Russian SOYUS satellite images, provided in analogue form, can be used in a similar way to colour infrared aerial photographs, with the benefits of large area coverage and low cost. The spatial resolution is from 5 to 10 m.

Satellite thermal infrared data

There are currently four satellite systems with thermal infrared sensors onboard. The main data set used is the Landsat TM band 6 data which lies in the 10.4 to 12.5 μm region of the electromagnetic spectrum. Numerous authors have used this data source to detect underground coal fires (Bhattacharya & Mukherjee 1991, Mansor et al. 1994, Prakash et al. 1995, Van Genderen et al. 1996, Wan & Zhang 1996). However, most authors have only used day-time data acquired between 9.30 and 10.30 a.m. For the China coal fire research, the authors have also used multi-temporal night-time thermal infrared data from Landsat TM in addition to the day-time data, thus easing the removal of solar heating effects which occur in day-time

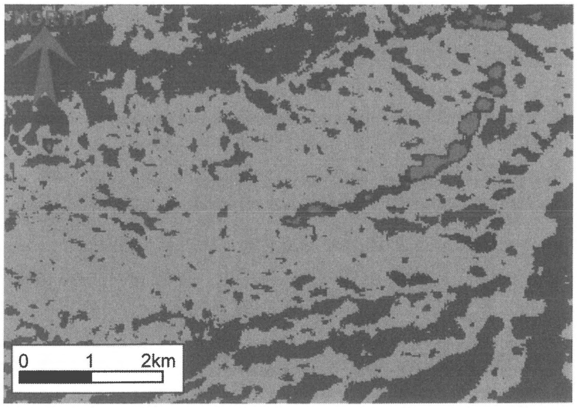

Figure 3. Night-time thermal infrared image acquired by the Landsat-TM over the Kelazha anticline coal-fire area in Xinjiang region on 7 April 1995. The image has been colour-coded and density-sliced. The areas in bright red indicate the location of underground coal fires. (For full colour reproduction of this figure, see Appendix at the end of this issue.)

imagery. A night-time thermal infrared image taken by the Landsat TM satellite over the Kelazha coal-fire area in the northwest is reproduced in Figure 3. The bright red spots are the coal fires occurring underground. However, as the spatial resolution of the thermal channel on Landsat TM is 120 m, very small, or very deep coal fires are often not detected. The new Landsat 7 ETM (Enhanced Thematic Mapper) that will be launched in 1999 will have a spatial resolution of 60 m, and should hence be able to detect much smaller coal fires. The 16-day repetitive cycle of Landsat makes this an ideal data source for routine monitoring of underground coal fires, both during day and night, and for checking the effectiveness of the fire fighting and extinguishing activities being carried out. The Advanced Spaceborne Thermal Emission and Reflectance Radiometer (ASTER) due for launch on 15 July 1999 onboard EOS spans the 8–12 μm region with five contiguous bands (Kahle et al. 1991) enabling the possibility of multichannel split-window thermometry at 90 m resolution.

In addition to Landsat, there are three other satellites acquiring data in the thermal wavelength bands. One is the NOAA-AVHRR (Advanced Very High Resolution Radiometer) which has several spectral bands in the thermal infrared region, e.g. channel 3 (3.55 to 3.93 μm), channel 4 (10.3 to 11.3 μm), and channel 5 (11.5 to 12.5 μm). The spatial resolution varies from 1.1 km at nadir up to 8 km at the border of the image. This data source has been extensively studied and used for forest-fire detection and for biomass burning at national, continental and even global scales, as the data is acquired globally on a daily basis, with both day-time and night-time data acquisition (Kaufman et al. 1992, Kennedy et al. 1994). The only published research to detect underground coal fires using NOAA-AVHRR data has been carried out by Mansor et al. (1994). These authors reported the potential capability of the AVHRR band 3 data to detect the subsurface coal fires in the Jharia coal field in India. They showed that the good thermal contrast between the coal-fire area and its surroundings in the night-time data could be used to detect coal fires. The fires did not reveal significantly higher thermal anomalies in the other thermal bands (channels 4 and 5). They used a simple density-slicing method to distinguish the location of the coal-fire areas, but the size of the coal-fire areas detected was not mentioned in their paper. In our research on the use of NOAA-AVHRR thermal data for detecting underground coal fires in northern China, no positive or reliable results have been obtained to date.

The third satellite data source used for thermal anomaly detection was from the ATSR (Along Track Scanning Radiometer) sensor, on board the ESA ERS-1 satellite. This operates in the thermal infrared wavelength centred at 11 and 12 μm (also at 3.7 μm in night-time mode) and has a spatial resolution of ca. 1 km. To date the results for the test sites in China have been disappointing using the single-source processing and interpretation approach.

Another satellite system with a thermal sensor currently in orbit is the Russian RESURS-1, which has a spatial resolution half-way between Landsat and the other systems mentioned above, namely 600 m. Although an order for multitemporal data coverage of the China coal-fire test area was placed in June 1996, no data have yet been received. Hence no evaluation as to its usefulness can be made as yet.

Satellite-based microwave data

The European Space Agency's ERS-1 and ERS-2 satellites have a Synthetic Aperture Radar (SAR) sensor operating in the C band on board, with a spatial resolution of approximately 25 m. These two satellites were flown in a so-called 'Tandem' model with a one-day interval between data acquisitions, so that using SAR interferometric techniques, a DEM can be produced, and using differential interferometry, very small vertical land-subsidence movements (in the order of centimetres) can be accurately measured. For a description of the concepts and applications of SAR

Figure 4. Land subsidence occurring as a result of underground coal fires, Helanshan Mountains. The cracks are typically 20 cm to several metres wide, up to hundreds of metres long, and 10 to 20 m in depth. The process is illustrated in Figure 5. (For full colour reproduction of this figure, see Appendix at the end of this issue.)

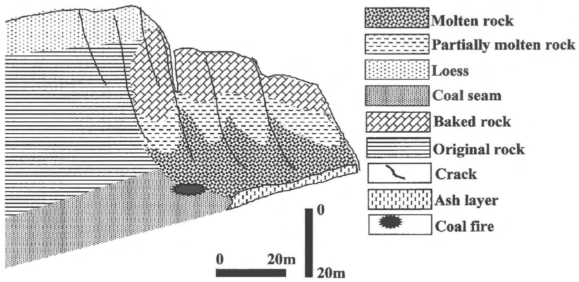

Figure 5. Schematic presentation of features related to land subsidence caused by a sub-surface coal fire. Once the coal seam starts to combust where it outcrops, it slowly burns out, and the commonly 10 to 20 m thick seam is reduced to a few centimetres of ash. Subsequent collapse of the overburden causes extensive cracking and opening of fissures through which fresh oxygen can reach the seam, which burns deeper and deeper with successive collapse of overburden.

Interferometry, see Gens & Van Genderen (1996) or Klees & Massonnet (this issue). As principal investigators to ESA, the authors have just acquired some imagery of the coal-fire area in the Helanshan Mountains of the Northern Ningxia Hui Autonomous Region. These will be used to quantify land-subsidence movements over the coming period. Figure 4 shows the land subsidence occurring in a coal-fire area, whilst Figure 5 describes the concept in diagram form.

Multi-sensor data fusion

The above section on single-sensor detection of coal fires has shown, that many individual remote-sensing systems provide useful data for detecting underground

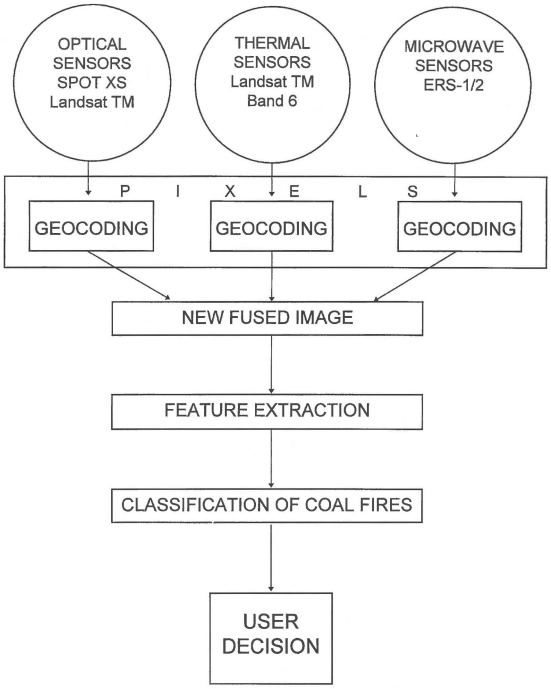

Figure 6. The system for pixel-based image fusion for detection of underground coal fires.

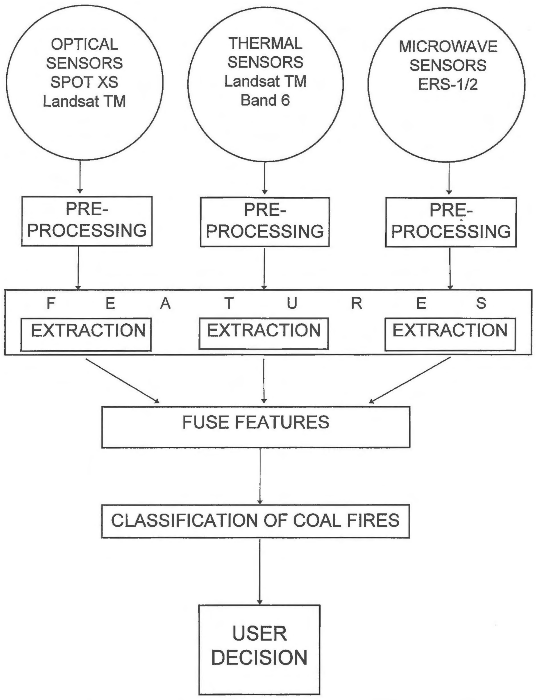

Figure 7. The system for feature-based data fusion for detection of underground coal fires.

coal fires, but that each data type only provides partial detection capability, and often only under specific conditions. Hence, in order to develop a cost-efficient methodology with higher detectability, a multi-sensor data-fusion approach is applied. It is the objective of multi-sensor data fusion to integrate complimentary information. There are three levels of fusion, namely pixel-based, feature-based and decision-based.

Image fusion can be defined as 'the combination of two or more different images to form a new image by using a certain algorithm' (Van Genderen et al. 1994, Pohl & Van Genderen 1998). Data or information fusion is a process whereby features are extracted and classified from both imaging and non-imaging data sources using probability theory to reinforce a common unambiguous interpretation of the features of interest, such as underground coal fires.

These concepts are pixel-based fusion, feature-based fusion and decision-based fusion. They are explained schematically in Figures 6, 7 and 8, respectively. The simplest fusion concept is pixel-based as depicted in Figure 6, showing different images to be combined in a new one, on which the underground coal fires are detected more reliably and easily. Of course, using this pixel-based fusion approach, each

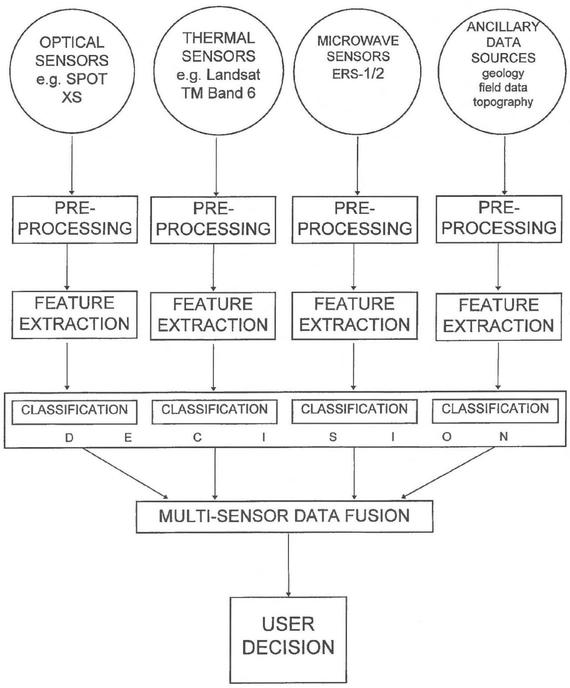

Figure 8. The system for decision-based information fusion for detection of underground coal fires.

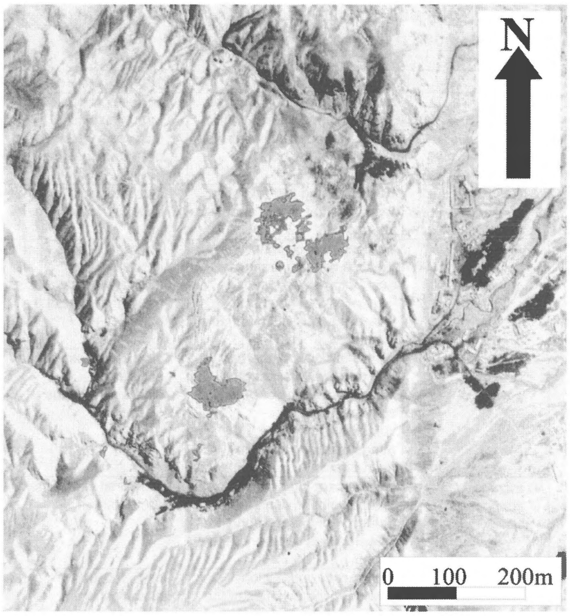

Figure 9. Example of feature-based image fusion for the detection of coal fires with respect to thermal anomalies derived from the thermal infrared image and the cracks shown in the colour infrared photograph. Paleo-coal-fire at Liuzhuangzi at top center (deep yellow; cf. Figure 2) is clearly distinguishable from present fires. (For full colour reproduction of this figure, see Appendix at the end of this issue.)

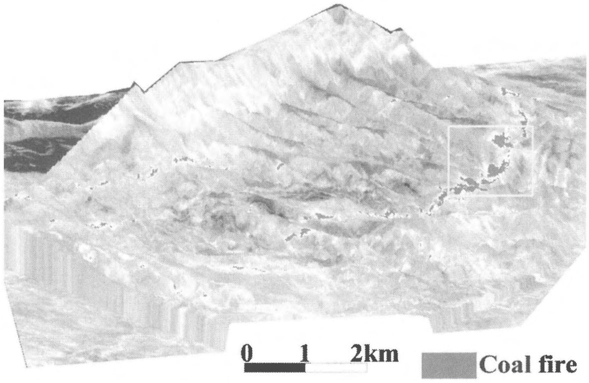

Figure 10. Airborne thermal infrared image data draped over and co-registered with the DEM to create a 3-D perspective view (due to the stretching at some places individual pixels can be seen) of Kelazha anticline coal-fire area (cf. Figure 3). Such products assist in the study of underground coal fires as they show the influence of topographic variables on the distribution of the fires. This view is looking in an ENE direction. Box outlines area of Figure 11. (For full colour reproduction of this figure, see Appendix at the end of this issue.)

individual image must be accurately geometrically corrected, in order that the two images co-register to sub-pixel accuracy. Parameters such as pixel size and orbit inclination must be corrected prior to fusion.

Examples of feature-based fusion as input to an overall Multi-Sensor Data Fusion System are shown in Figures 9 and 10. Figure 9 is a combination of a colour infrared photograph digitised by scanning and a thermal infrared image. In the colour infrared photograph, shown in Figure 2, the cracks and the burnt rocks caused by the underground coal fires are very clearly visible. In the thermal infrared image, only the thermal anomalies of the active coal fires are detectable. The two images were first geocoded, then the thermal infrared image was resampled to match the scanned photograph. The areas with a pixel value larger than 200 in the thermal infrared image were taken as fire areas. To minimise the confusion of the detailed terrain features only the 'features' of thermal anomalies in the thermal infrared image were included in the fusion excluding all other features of the thermal infrared image. Considering the relationship between the thermal anomalies, burnt rocks and cracks, the spreading direction of the underground coal fires can be derived. By integrating information from the DEM with the position of the outcrop of the burning coal seam, taken from the image, the depth of the coal fires can be estimated by using the dip-angle model (Saraf et al. 1995, Cassells & Van Genderen 1995, Peng et al. 1997). It is suggested by one of our authors to use the differences in the colour of the burnt rocks on the colour infrared photographs to distinguish between the burnt rocks caused by active coal fires and by paleo-fires. The burnt rocks caused by paleo-fires are normally deep yellow and those related to the active coal fires are light yellow due to the fact that the light-coloured minerals such as sulphur and salmiac are easily weathered. These colour differences are also clearly shown in Figure 9, with the paleo-coal-fire at Liuzhuangzi at the top centre of the image in deep yellow colour, which can easily be distinguished from the active coal fires associated with thermal anomalies.

Another application of feature-based fusion, presented in Figure 10, has made use of the airborne night-time thermal infrared data, from which all subsurface coal fires have been extracted by setting a threshold, and then marked in red. The result has then been draped over the DEM to produce this image to allow the interpreter to study the influence of the slope, aspect, altitude and relief on the occurrence and distribution of underground coal fires. These aspects are of importance to coal-fire prevention plans and subsequent monitoring.

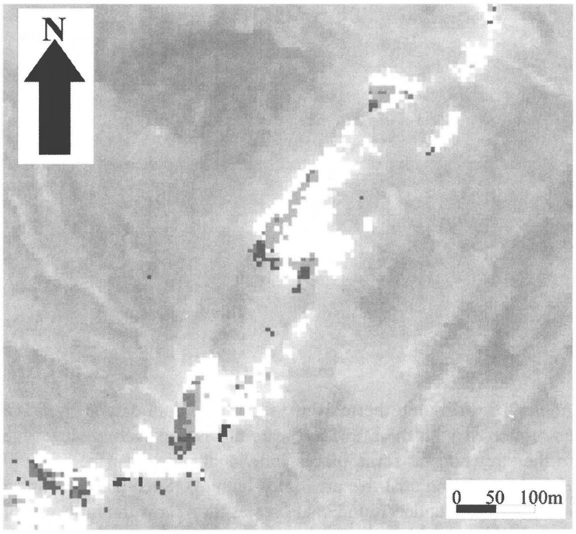

Figure 11. Example of decision-based image fusion for the detection of different intensive coal fires. The red areas represent the most intensive coal-fire areas derived from the 3–5 μm data. The green areas represent the middle-intensive coal fires derived from the day-time thermal infrared data of 8–12.5 μm. The white areas are the low-intensive coal fires derived from the night-time thermal infrared data of 8–12.5 μm. The blue areas are the intensively solar-heated area. Individual pixels can be seen on the image. For location see Figure 10. (For full colour reproduction of this figure, see Appendix at the end of this issue.)

Table 1. Results and benefits of multi-sensor data fusion for the detection of underground coal fires.

Results	***General Advantages***	***Operational Benefits***
• *Robust operational performance*	one sensor can continue to contribute information, whilst others are unavailable or lack coverage of the coal fire areas	- allows continued operation - increases possibility of detecting coal fires
• *Enhanced spatial resolution*	by pixel fusing low and high resolution date, can "sharpen" images	- aids interpretation and detection of fire areas
• *Enhanced temporal coverage*	by using multiple satellites, the time between image acquisitions is reduced. Enhances likelihood that an image is acquired under ideal conditions	- day/night, all weather capability - increased possibility of underground coal fire detection
• *Enhanced spectral coverage*	combining optical, thermal and microwave sensors increases chance of detecting coal fires. Also less vulnerable to atmospheric/weather/day-night effects	- increases classification accuracy - allows continuous operation
• *Increased confidence*	each sensor type and image source helps to confirm detection of underground coal fires; reduces number of false alarms	- increased classification accuracy
• *Improved detection*	multisensor data fusion increases the chances of the underground coal fires being detected	- more reliable classification - higher accuracy
• *Reduced Ambiguity*	joint information from multiple data sources reduces the number of alternative hypothesis about whether a feature is really a coal fire or not	- faster decision making - increased reliability of the results

An example of decision-based data fusion is presented in Figure 11. Airborne thermal data from 3 to 5 μm acquired during the day, and day and night-time 8 to 12.5 μm data were used. The thermal anomalies are derived by setting thresholds. The thermal anomalies depicted in the night-time data show the largest areas of coal fires due to the better thermal contrast. Because of the solar heating effect and the higher setting of the blackbody reference temperatures, less intensive fires may be obscured on the day-time thermal image and the resulting coal-fire area is smaller. As the peak of emitted radiation shifts to shorter wavelengths, the very intense coal fires can also cause thermal anomalies in the shorter thermal infrared image of 3 to 5 μm. By means of data fusion techniques, the thermal anomalies derived from the multispectral and multitemporal data can be combined. The spatial characteristics of the thermal anomalies and the underground coal-fire spreading direction can then be analysed (Zhang 1998).

In our example, we used the pixel based fusion approach to enhance the burnt rock and active coal-fire areas. If the coal-fire features were detectable, the feature-based fusion approach was taken to analyse the spatial relationship of the direct and indirect indicators of the coal fires. Decision-based fusion makes it possible to analyse the spatial characteristics of the coal fires of different intensity.

By using the techniques and approaches described, an overall, integrated Multi-Sensor Data Fusion System is being developed. This is explained in diagrammatic form in Figure 12 which shows a three-level fusion system. The first level uses the very cheap NOAA-AVHRR data, which provide daily global coverage together with data from the VEGETATION sensor on-board SPOT-4 (from 1998) and data from the thermal channel of ERS-1 ATSR. Data from the RESURS-01 satellite's thermal channel with spatial resolution of 600 m will also be used once available. From these sources, a weekly or monthly analysis of new 'hot spots' or areas of burnt rock can be obtained. By overlaying this on a coal-geological map of the area, all 'false alarms' can be filtered out (e.g. 'hot spots' not occurring near coal-bearing areas). Then, at the second level of detail, the medium-resolution Landsat TM day- and night-time optical and thermal infrared data are used to more accurately confirm the coal fires detected in level 1 and to delineate and meas-

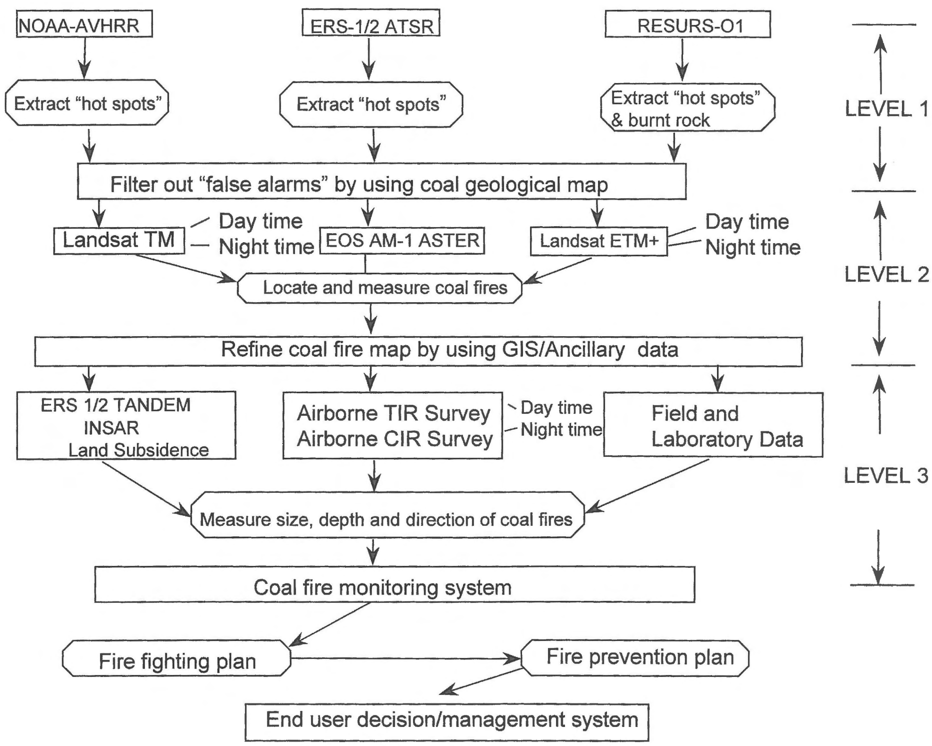

Figure 12. A three-level Multi-Sensor Data-Fusion System developed by ITC to study location, size and depth of underground coal fires for monitoring and management purposes.

ure their size and extent. Other data sources for the second level in the near future are from ETM+ and ASTER. The Enhanced Thematic Mapper (ETM+) on board Landsat-7 due for launch on 15 July 1999 will offer a 60 m spatial resolution thermal band and improved radiometric calibration. The Advanced Spaceborne Thermal Emission and Reflectance Radiometer (ASTER), which will also be launched on 15 July 1999, spans the 8 to 12 μm region with five contiguous bands (Kahle et al. 1991) enabling the possibility of multichannel split-window thermometry at 90 m resolution. In addition to the thermal infrared coverage, ASTER offers three visible and near-infrared channels in the range of 0.52 to 0.86 μm at 15 m resolution, and six short-wavelength infrared channels in the range of 1.6 to 2.430 μm at 30 m resolution. At the third level of data and information fusion, detailed airborne surveys using colour infrared and thermal infrared (day- and night-time imagery) data, together with ancillary data such as DEMs, field measurements, and land-subsidence measurements from InSAR, are used to make an overall classification of the size, depth and direction of the coal fires. All these data and information are put into in a GIS for use in the operational monitoring system.

On the basis of this information system, fire-fighting plans can be drawn up together with a fire-prevention plan, as most local coal fires are presently caused by mining activities, and not by natural spontaneous combustion. The whole system can then be used in a multi-temporal mode, by regular updating of the remote-sensing inputs. The results and benefits of a multi-sensor data fusion system for the detection of underground coal fires are outlined in Table 1.

Conclusions

An increasing number of Earth observation satellites provide data for detecting underground coal fires, each covering a different portion of the electromagnetic spectrum at different spatial, temporal and spectral resolutions. For the full exploitation of such increasingly sophisticated multi-source data, advanced analytical or mathematical data-fusion techniques need to be developed. As each individual data source only provides part of the information required for decision making, the types of pixel, feature and decision-level fusion techniques discussed in this paper can contribute greatly to the detection of underground coal fires.

Using the Multi-Sensor Data-Fusion approach described in this paper for the detection of underground coal fires is expected to result in an improved system reliability. As the multiple satellites and sensors relied on have a certain inherent redundancy, it will be less critical in the future if one of these were to fail. It will also simplify the investment scheme of the Chinese Ministry of Coal Industry to set up its operational coal-fire detection, measurement, monitoring and extinguishing system.

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