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Monitoring coal fires in Datong coalfield using multi-source remote sensing data

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Abstract: Numerous coal fires burn underneath the Datong coalfield because of indiscriminate mining. Landsat TM/ETM, unmanned aerial vehicle (UAV), and infrared thermal imager were employed to monitor underground coal fires in the Majiliang mining area. The thermal field distributions of this area in 2000, 2002, 2006, 2007, and 2009 were obtained using Landsat TM/ETM. The changes in the distribution were then analyzed to approximate the locations of the coal fires. Through UAV imagery employed at a very high resolution (0.2 m), the texture information, linear features, and brightness of the ground fissures in the coal fire area were determined. All these data were combined to build a knowledge model of determining fissures and were used to support underground coal fire detection. An infrared thermal imager was used to map the thermal field distribution of areas where coal fire is serious. Results were analyzed to identify the hot spot trend and the depth of the burning point.

Key words: Landsat; unmanned aerial vehicle; infrared thermal imager; coal fire; Datong coalfield; remote sensing

1 Introduction

Underground coal fire refers to coalfield fire or mine fire usually caused by human factors or spontaneous combustion. It often occurs in China, United States, Australia, India, and Indonesia, and has become a global catastrophe. Coal fire causes a huge waste of energy and produces soot and harmful gases, such as SO_x, CO, and NO_x, that seriously pollute the air and threaten the health of local residents [1]. Its byproducts, the greenhouse gases CO_2 and CH_4, exacerbate global warming. Underground coal fire has also led to surface subsidence and produced a large number of surface fissures, especially when the burning is severe, thereby prompting geological disasters. Thus, the elimination of coal fire remains a crucial challenge today. Researchers and governments have focused on coal fire problems and developed various monitoring methods based on remote sensing [2−12]. However, such methods are applicable only to large, severe, and open burning fires. Numerous coal fires burn underneath the Datong coalfield because of indiscriminate mining. The lack of data is exacerbating the problem, which in turn makes the monitoring more difficult. The situation becomes even more serious when surface fissures, the working face, and goafs are interconnected and allow the circulation of air that fans underground coal fire. As such, the technical problem is the quick and precise location of the burning points of the coal fire and the determination of their extent throughout the entire coalfield region, which possibly covers as large as thousands of square kilometers. Based on the characteristics of the coal fire in the Majiliang mining area, Landsat images, unmanned aerial vehicle (UAV), and infrared thermal imager were employed to monitor the underground coal fire in this region and develop a ground-air integration analysis of the underground coal mine fire detection technology through field monitoring, surface analysis, mechanism exploring, modeling, and system development.

2 Studied area

The Datong coalfield is located in northern Shanxi

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Province, China, approximately from 39°52′ to 40°10′ north latitude and 112°49′32″ to 113°9′30″ west longitude. It has a complex terrain with an average altitude of more than 1200 m. The studied area is located in the Majiliang mining area, as shown in Fig. 1. The Datong coalfield is composed of fields that originate from various geological periods. Its northeastern section is characterized by upper Jurassic coal-bearing strata of 772 km^2 and the rest by lower Carboniferous and Permian coal-bearing strata of 1739 km^2. Coal fires mainly occur in the No. 2 Jurassic coal seams in the mining area, 30 m to 130 m below the surface, with an average thickness of about 1 m. This coal seam is seriously damaged by small illegal coal mines. Furthermore, the abandoned roadways connect the underground coal with the ground surface, one of the main reasons for the occurrence of underground coal fires. In addition, given the low mining depth and the weak roofs caused by coal fires, many ground fissures are found across the area, through which air enters and circulates underground, thereby aggravating underground coal fires.

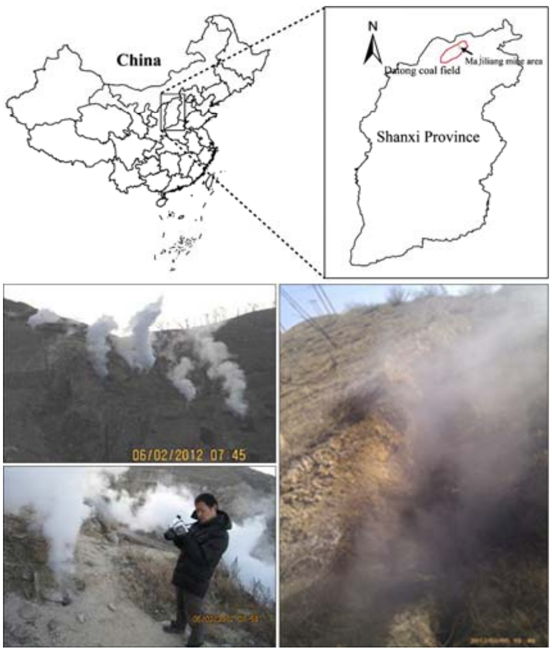

Fig. 1 Location of Majiliang mine area and related coal fire photos

3 Multi-source remote sensing monitoring

To meet the requirements of Majiliang coal fire monitoring, the study was conducted on different scales. 1) Using the Landsat thermal infrared band, the temperature filed distribution of the entire study area was established and the whole area was classified according to its temperature. This procedure helped to determine roughly where the underground coal fires exist. 2) Using UAV technology, a high-resolution (0.2 m) image of the studied area was obtained. Based on the characteristics of the ground fissures caused by underground coal fire, a new method was introduced to monitor underground coal fires. 3) For areas in which the underground coal fire was serious, a thermal infrared imager was employed to build a high-precision regional surface temperature distribution. The spatial variability of the temperature distribution was analyzed to determine the location under which points coal fires are burning.

3.1 Coal fire monitoring using Landsat thermal infrared band

The use of the Landsat thermal infrared band is one of the most important means of detecting and monitoring coal fire [13,14]. At present, the main algorithms used in surface temperature retrieval include the radiative transfer equation, the mono-window algorithm, and the single-channel method [15−17]. Considering the available datasets in our studied area and the previous research in Ref. [18], the mono-window algorithm with Landsat TM/ETM was employed in the retrieval of land surface temperature. Landsat ETM imageries in 2000 and 2002 and Landsat TM imageries in 2006, 2007, and 2009 were selected to obtain the surface temperature in each period (Fig. 2).

Figure 2(a) shows the true color composite image of the studied area on September 25, 2002 at a resolution of 15 m. The western part of the studied area is mainly composed of buildings, so that the corresponding areas in Figs. 2(b)−(f) show red or yellow colors, which represent high surface temperature.

The eastern part of the studied area is mainly a wasteland with sparse vegetation and varied surface temperature. The high temperature parts show a southwest to northeast trend, where the temperature can be higher than the surrounding low temperature areas by around 10 °C to 30 °C. Such trend suggests that coal fires are burning underground. An obvious plaque effect exists in the temperature images caused by the low spatial resolution of the Landsat thermal infrared band. This effect limits the ability of Landsat in monitoring the coal fires underneath the Datong coalfield as coal fires in this region are usually of small sizes. However, the method provides valuable information on the temperature distribution in the coalfield. Combined with land use charts, Landsat images help roughly determine target regions where underground coal fires exist.

3.2 Coal fire monitoring using UAV

Underground coal fires weaken roofs and cause serious collapse, thereby producing ground fissures. These ground fissures in turn provide the air that fans and accelerates underground coal fires, thereby forming the vicious circle of "coal fire—ground fissure—collapse". Therefore, more ground fissures occur, and the width of which usually becomes broader. Through the spatial distribution of ground fissures, the location of underground coal fires can be determined. Moreover, by filling ground fissures, the amount of air that enters underground is reduced and the underground coal fires are eliminated. High-resolution remote sensing imagery can cover a wide area and provide up-to-date images containing rich information. As such, the method is suitable in investigating huge ground fissures across wide areas. However, various reasons limit the use of satellite remote sensing in monitoring coal fire and ground fissures, such as long revisit periods, frequent cloud contamination, insufficient resolution for small fissures, and the availability of archived data only during summer when rich vegetation covers ground fissures. By contrast, compared with satellite remote sensing, UAV has many advantages. It is more flexible in terms of working time and region, has higher spatial resolution (more than 0.2 m), and is cost effective. It provides much better image data for ground fissures. Figure 3 shows how UAV is used in monitoring underground coal fire.

Figure 4(a) shows the 0.2 m resolution UAV image of the studied area. Figure 4(b) shows the enlarged ground fissures area and Figure 4(c) shows a photo of this fissure taken by a camera. Smoke is emitted by the hole, containing pungent hydrogen sulfide, SO_2, and other harmful gases, meaning that the fissure serves as a passageway by which air reaches underground.

According to the texture information, linear feature, and brightness of the ground fissures, a knowledge model was established to facilitate the automatic extraction of ground fissures. The steps are as follows. 1) Occurrence-based variance, co-occurrence-based variance, data range, and contrast filters are used for the UAV image to obtain the texture information in the fissured area by a moving window. 2) Principle component analysis (PCA) and Fisher linear discrimination analysis are then performed to extract the

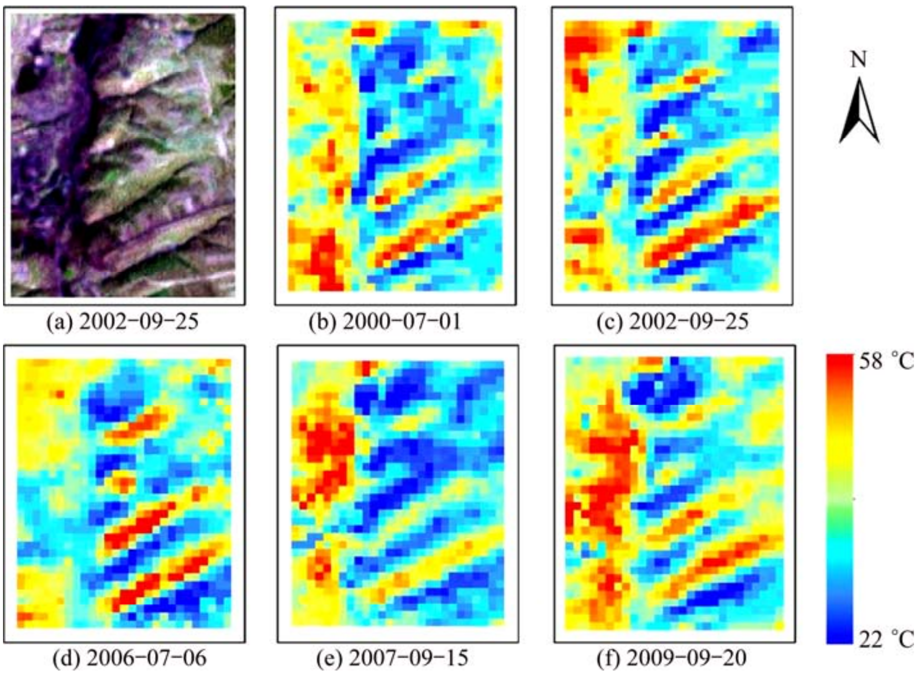

Fig. 2 R(Band 5), G(Band 4) and B(Band 3) composite images with 15 m spatial resolution (a) and temperature distribution retrieval by Landsat thermal infrared band with 60 m spatial resolution (b)−(f)

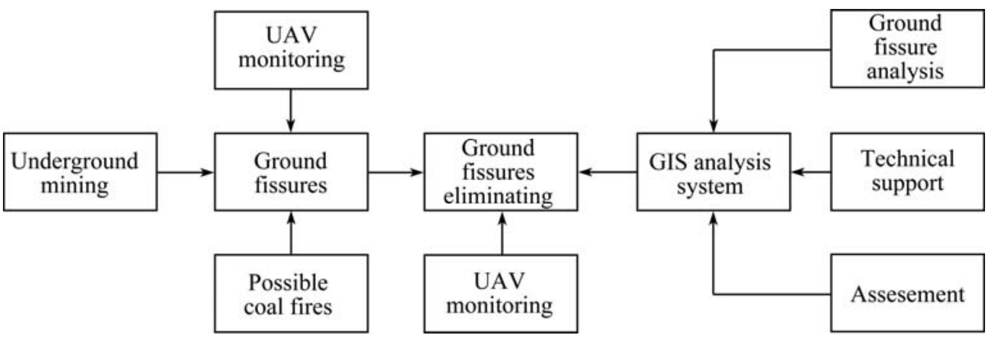

Fig. 3 UAV-based coal fire monitoring

linear features of the area. At the same time, the fractal dimensions of the fissures, houses, and ridges are computed to determine fissures from other surface features. 3) A gray level statistic is then made for the UAV image to obtain gray value samples of real fissures recorded by GPS. These characteristics are compared with those not belonging to the ground fissures to determine the separate thresholds. 4) Based on the model established in Steps 1 to 3, ground fissures are automatically extracted using ERDAS software. Figure 5 shows a flowchart of the ground fissure extraction using a UAV image and Fig. 6 shows the results.

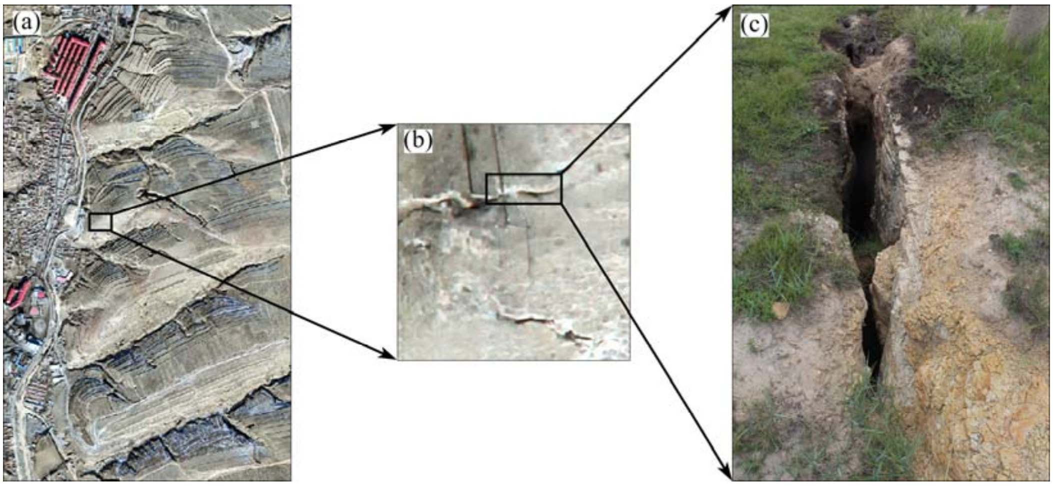

Fig. 4 UAV image with 0.2 m spatial resolution able to capture ground fissure in coal fire regions

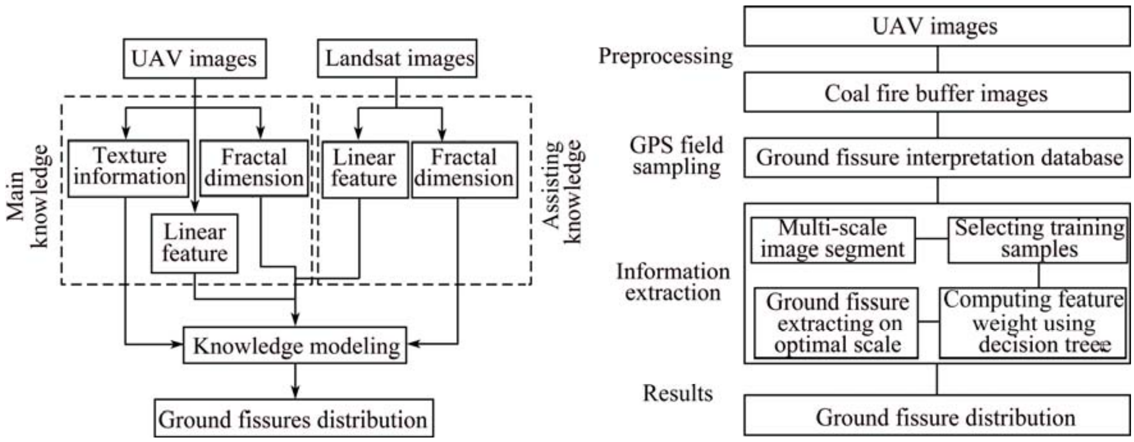

Fig. 5 Flow charts of ground fissure extraction using UAV images

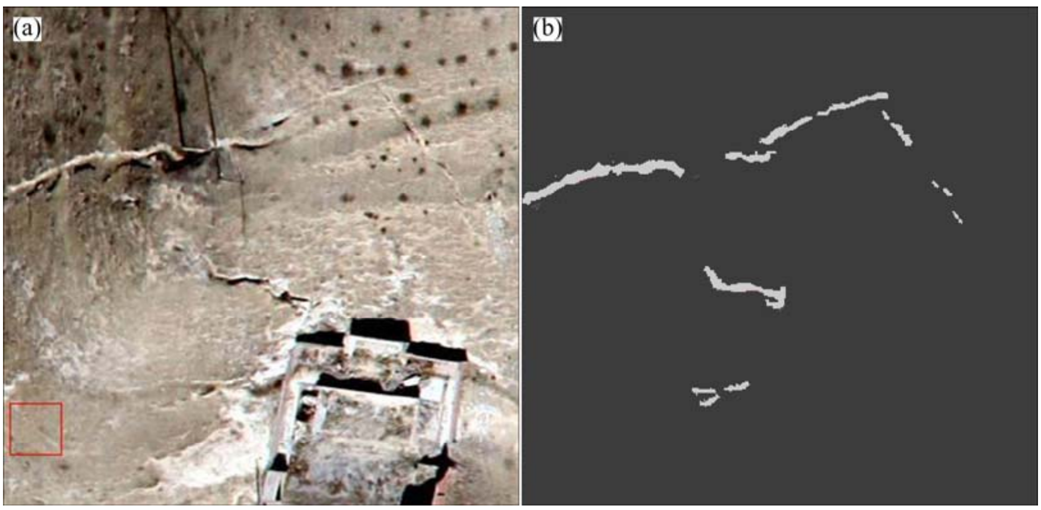

Fig. 6 Results of ground fissure extracting based on knowledge model: (a) UAV image; (b) Extracted fissures

3.3 Coal fire monitoring using infrared thermal imager

3.3.1 Surface temperature field analysis of spontaneous combustion mountains

An infrared thermal imager has several advantages. It can be transported conveniently and it is highly accurate in measuring temperature. It can build a surface temperature map, analyze coal combustion regions, and precisely locate burning points to photograph key regions of coal combustion. In this study, a Th9100 Wri8.5 infrared thermal imager was used in implementing ground thermal infrared monitoring through a top-down parallel partition from the summit of the coal spontaneous combustion mountain and in collecting thermal infrared photos. The collected thermal infrared images were stitched in door according to their spatial coordinates. The results are shown in Fig. 7.

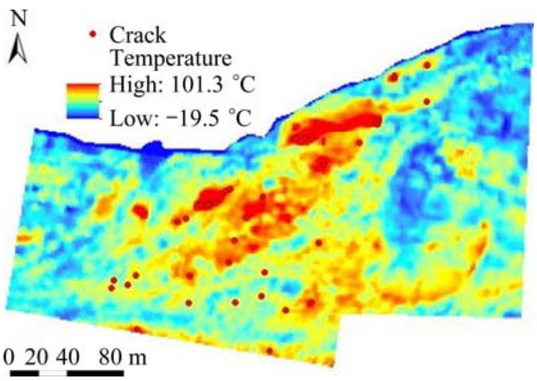

Fig. 7 Mosaics results of temperature (part of mountain)

The temperature of the spontaneous combustion mountain is obviously higher than that of the surrounding environment, in which spontaneous combustion does not exist (about −23 °C). Such temperature distribution suggests that burning occurs in the mountain. On this basis, the "second-order effect" methods of spatial data analysis called "Getis−Ord General G_i^*" [19] are used to analyze the clustering distribution of the surface temperature in the coal fire region of the Majiliang coal mining area to study the distribution trend of the high-temperature and low-temperature zones. The Getis−Ord G_i^* can be expressed as follows:

$$G^*(d)=\sum_{j=1}^{n}W_{ij}(d)X_j \Big/ \sum_{j=1}^{n}X_j \quad (1)$$

For convenient interpretation and comparison, the above equation should be standardized as follows:

$$Z(G^*)=G_i^*-E(G_i^*)/\sqrt{\mathrm{Var}(G_i^*)}$$

where $E(G_i^*)$ and $\mathrm{Var}(G_i^*)$ are the mathematical expectation and variance of G^*, respectively, and $W_{ij}(d)$ is the spatial weight defined by the distance role. The value is 1 when the space is adjacent and 0 when the space is not adjacent. The Z score is the statistical value of $G^*(d)$ in Getis−Ord G_i^* for each element of the dataset. For statistically significant positive Z scores, the higher the value is, the closer the high temperature (hot spot) clustering is, which belongs to a high value spatial agglomeration (hot spot area). For statistically significant negative Z scores, the the value is, the closer the low value (cold spot) clustering is, which indicates that the location of values around i is relatively low (below average). i belongs to a low value spatial agglomeration (cold spot area).

As Fig. 8 shows, the surface temperature in the coal fire region of the Majiliang coal mining area exhibits a strong regularity in its spatial variation. The distribution of its high-temperature and low-temperature zones is relatively concentrated. The spatial distribution of the mountain surface temperature shows an obvious aggregation, which indicates that deep and shallow layers of coal combustion zone exist underground.

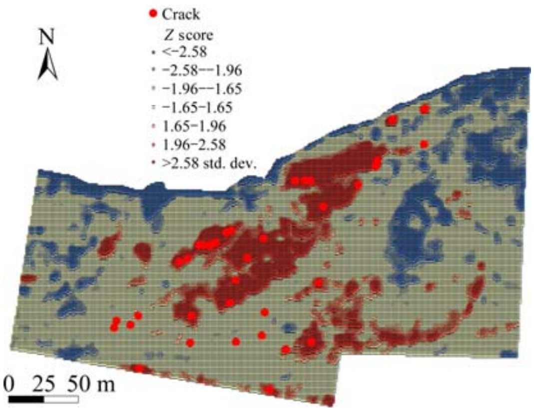

Fig. 8 Cold hot spot analysis

Fume emission is obvious throughout the mountain, especially around the mouths of cracks, accompanied by H_2S and other irritant gases, which are suspected of being external expressions of an underground coal combustion zone. A handheld GPS was used to collect the coordinates of each crack in the mountain, as shown in Figs. 7 and 8. As the figures show, the temperature in the cracks is higher than that on the surrounding surface (Fig. 9). However, the temperature around the cracks is far lower than that around non-cracks, which shows that the cracks indeed serve as channels of air exchange between the atmosphere and the coal combustion zone inside the mountain. The internal gases are discharged through the cracks, but they do not constitute a vertical form of the internal combustion point on the surface.

3.3.2 Location of coal fire points inside spontaneous combustion mountain

The surface temperature field analysis of the spontaneous combustion mountain makes clear the surface characteristics and temperature distribution of the combustion process inside. It also provides basis for the location of the coal fire. However, research on the burning points of the underground coal fire involves the kinetic parameters of the coal oxidation reaction, temperature, and oxygen concentration of the coal mine at different depths, heat release rates of coal, thermal conductivity, and permeability of mountain rocks and soils. As such, no one general model can solve the problem, based on the study of the heat production—heat dissipation balance calculation equation of the spontaneous combustion depth of the inter gangue hill [20]. This study modifies the equation to estimate depth of the ignition point of the underground coal fire.

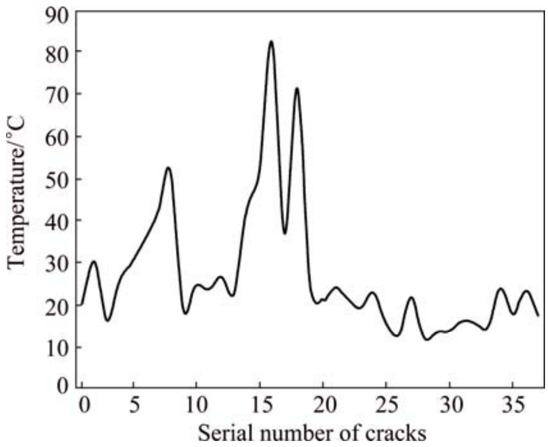

Fig. 9 Temperature distribution value in ground cracks

Considering that the studied area is mainly filled with coal combustion, the equation was modified by canceling the gangue carbon content correction value. The new coal combustion depth calculation equation is as follows:

$$L=g(t_f-t_a)/(KK_D) \quad (2)$$

where L is the spontaneous combustion depth; g is the heat transfer coefficient of convection, the value of which for natural air is generally 20 W/(m·°C); t_f is the mine surface temperature; t_a is the atmospheric environment temperature; K is the conversion coefficient; and K_D is the coal particle correction coefficient. Among these variables, the value of the gangue thermal conductivity coefficient is modified to rock thermal conductivity coefficient. The details refer to Ref. [21]. This value is set to be 3 W/(m·K).

According to the value of each parameter, the results are as follows. When the surface temperature is the highest (101.3 °C), the burning depth of the underground coal fires is about 1.87 m. When the surface temperature is 0 °C, the burning depth of the underground coal fires is about 7.33 m. When the surface temperature is equal to or lower than the air temperature, no spontaneous combustion phenomenon exists. On this basis, the logarithmic and power functions with a relatively high fitness are selected to fit the functions of the spontaneous combustion temperature and the depth of underground coal fire point, as shown in Fig. 10. The depth map of the internal spontaneous combustion point is shown in Fig. 11. First, in the graph, the white region surrounded by the blue region is the region with the shallowest ignition depth. The white region surrounded by the red region is the region with the deepest ignition depth. Second, the calculation of underground coal combustion depth is closely related to rock properties, coal chemical composition, impurity content, and a large number of other parameters. Many uncertain factors influence the values of these parameters and must be researched further to improve the accuracy of the results.

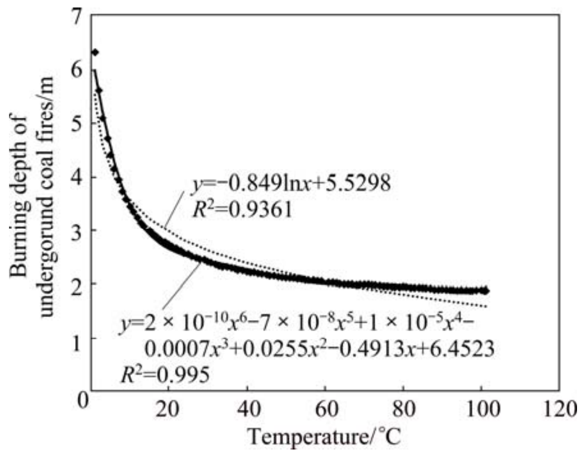

Fig. 10 Fitting function between surface temperature and ignition point depth

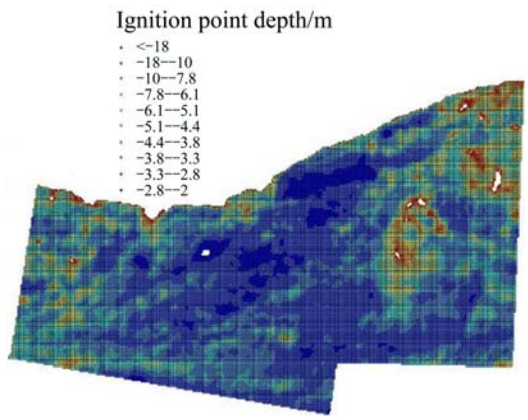

Fig. 11 Depth of underground burning coal fires

4 Conclusions

1) The Landsat thermal infrared band can macroscopically reflect the spatial distribution characteristic of the solar radiation temperature in the coal fire region and provide a target area for the accurately positioning of the coal fire region.

2) The Landsat thermal infrared band is also an ideal source of data for coal fire monitoring, because the unmanned aircraft process is flexible in photographing. The images produced have higher resolution, the distribution information on the centimeter-level width of the cracks in the coal fire region can be extracted through images obtained by the optical camera carried by the unmanned aircraft. The technique assists in the assessment of the conditions of the underground coal fire, and it serves as a reference in filling the cracks and in controlling underground coal fires.

3) A surface temperature field model can be built from the temperature image of the coal combustion region photographed by the infrared thermal imager. The surface temperature field variation caused by the burning of coal fire can be analyzed on a small scale to make inferences on the more general issues of coal combustion characteristics and ignition depth, which in turn served as reference for locating the ignition points of the coal fire region.

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大同矿区煤火多源遥感监测

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摘 要：大同矿区由于古窑开采、小煤窑私挖滥采形成了众多在地表浅层燃烧的暗火火区。针对这些火区特点，利用 Landsat TM/ETM 温度反演、无人机和地面红外热像仪等集成分析技术监测马脊梁矿煤火区。利用 Landsat TM/ETM 影像提取 2000 年、2002 年、2006 年、2007 年和 2009 年 5 个时期的煤火区热场分布信息，分析其变化过程，圈定煤火区的大致范围；利用无人机搭载光学相机拍摄火区的高分辨率影像，结合煤火区地裂缝的纹理、线特征和灰度值等信息，建立知识模型，提取煤火燃烧区的构造裂缝，为探测、治理地下煤火提供了依据；利用红外热像仪采集煤火燃烧重点区域的温度场信息，进行热点趋势和着火点深度分析，为确定煤火区燃烧点提供依据。

关键词：Landsat；无人机；红外热像仪；煤火；大同矿区；遥感

(Edited by Yun-bin HE)