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REMOTE MONITORING OF SUBSURFACE HEATINGS IN OPENCUT COAL MINES

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ABSTRACT: The detection and monitoring of spontaneous combustion (sponcom) events in opencut coal mines are significant hazard management issues. Currently, the only way of locating sponcom incidents is by manual inspection, whether by visual examination or by use of hand-held thermal cameras, often putting personnel at risk. These inspections are also limited in terms of access and coverage. Therefore, there is a need to implement a convenient remote means to detect and monitor the state of subsurface heatings in opencut coal mines over extended areas for significant periods of time. A versatile self-contained imaging system has been developed that is deployed using an unmanned aerial vehicle. The system eliminates the safety hazard of personnel accidentally entering hot ground and being exposed to toxic gases often associated with heatings. Results obtained from the imaging system is presented, which generates thermal and visible geo-referenced images that can be overlaid onto a digital map of the surveyed area. The data allow rapid detection and accurate localisation of anomalous heat levels within target areas that can be updated on the mine plan for management purposes, and thus enables mitigation strategies to be monitored for effectiveness.

INTRODUCTION

Management of self-heating of coal is an important issue for safety and productivity of open cut coal mining. There are a limited number of methods for effective monitoring of associated ground heating and outbreaks of spontaneous combustion, due to the often large areas that require regular inspection. Traditionally, monitoring is performed via spot inspections by qualified staff or via infrequent manned aerial thermal imaging surveys, either of which involves OH and S risks to staff and/or expense prohibiting regular deployment.

Unmanned aircraft systems (UAS) and lightweight, low-cost thermal imaging cameras have become commercially available in recent years and provide an alternative monitoring solution. In combination they provide a cost-effective solution to the challenge of undertaking sufficiently regular thermal imaging surveys for management of coal-related ground heating and spontaneous combustion outbreaks (Vasterling, *et al.,* 2010a, 2010b; Sheng, 2010).

CSIRO has developed a proof-of-concept lightweight imaging payload deployed on a UAS that is capable of automated mission-based mapping of target areas. The system has been trialled at non-active coal mine workings in which residual heatings persist and thereby present realistic field-trialling scenarios. This paper details the basic configuration of the system used together with imaging results from these preliminary trials, thereby demonstrating the potential of the system for general use within the industry to improve detection, safety and cost effectiveness of this novel mode of spontaneous combustion management in open cut coal mines.

PROTOTYPE SYSTEM

UAS-based mapping is a relatively new technology that is being rapidly adopted in numerous commercial contexts, and is receiving growing interest from the mining industry for the safety and productivity gains that can be provided. At present, relatively few UASs offer the facility for autonomous operation, instead being operated remotely by qualified pilots. Furthermore, application of these systems to specific industries often warrants an OEM-based approach to permit a tailoring of the UAS to the payload being carried, which in turn warrants tailoring to the specific application area. CSIRO has developed a proof-of-concept system which combines an autonomous UAS with OEM-modifications to support a thermal imaging payload designed for aerial surveying of mining operations. The system (Figure 1) consists of a self contained imaging payload carried by a commercially available UAS.

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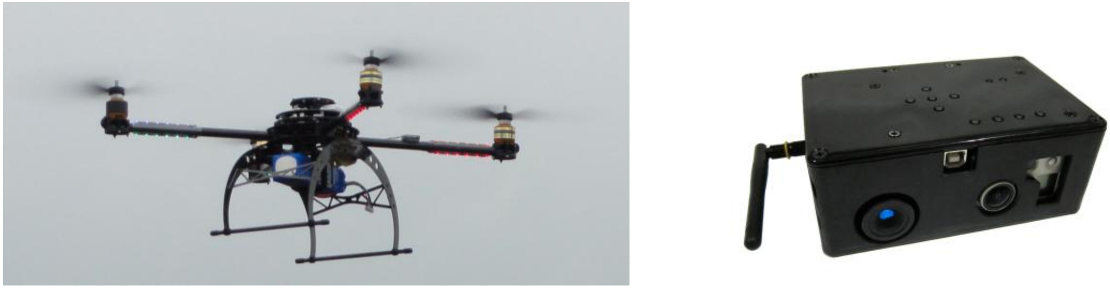

Figure 1- UAS and imaging payload

The UAS has the following specifications:

- autonomous GPS-waypoint-controlled flight (see Figure 2);
- wholly battery powered;
- durations of approximately 10-15 min per mission, but unlimited in the number of missions;
- a portable wireless base-station for mission control; and
- a camera mounting system.

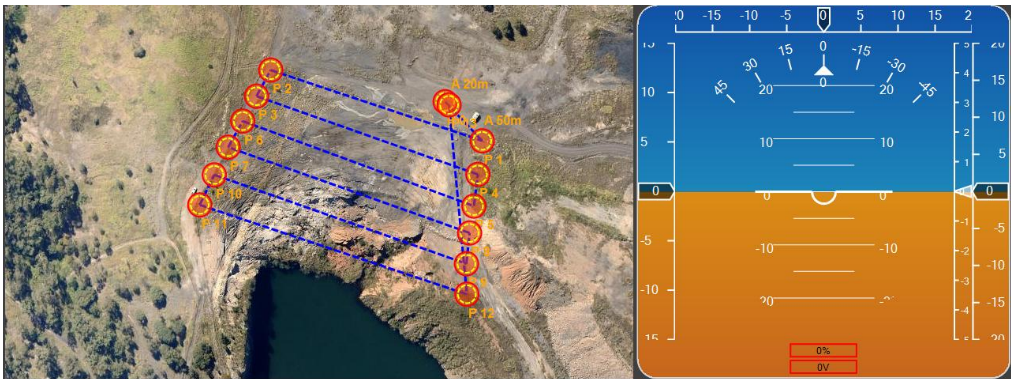

Figure 2 - Screenshot from base-station software application illustrating waypoint-planning facility for imaging-path planning

The imaging platform is a self-contained imaging payload consisting of:

- a thermal infrared (TIR) analogue video camera employing an uncooled micro-bolometer sensor array;
- a digital video recorder to record the TIR camera video signal;
- a visible-band spectrum digital video camera; and
- a self-contained battery power source.

FIELD TRIALS

An example false-colour overlay image of thermal activity of old mine spoil is shown in Figure 3, in which ground heating is readily discernable. The yellow and orange regions represent temperatures in the range of roughly 60^{o}C through to 200^{o}C, whereas the blue regions are of order 20^{o}C to 30^{o}C. These temperatures correspond to spot surface and sub-surface measurements taken using hand-probes since the TIR images in the present system are not calibrated for temperature.

The utility of aerial TIR image overlay is immediately evident from this particular field example. The boundaries and extent of heating are readily discernible which would otherwise only be partially detected from accompanying ground-level visible expressions such as ground sweating and fume emissions. Furthermore, smaller scale features that may be easily missed by visual inspection are prominent in the

TIR overlay; the regions marked by red arrows demonstrated clear expression of heating during ground-based inspections, however the small region indicated by the blue arrow did not show any visible expression of heating and would otherwise have not been detected in establishing the extent of the sub-surface heating progress.

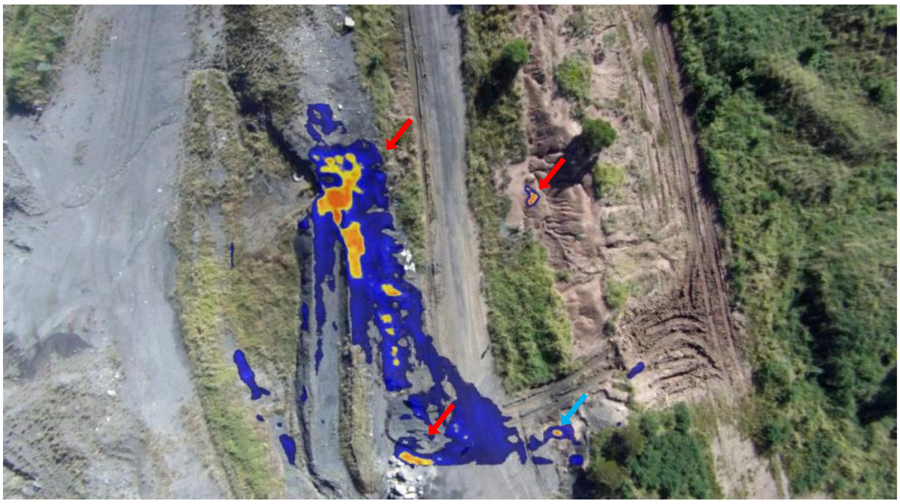

Figure 3 - Thermal and visible-band overlay image of old mine spoil

Results of a test of the capability to create mosaics of overlapping images are shown in Figure 4. This was taken at surface workings of a decommissioned coal mine using an artificial heat source (an electric element operating at 150^{o}C), readily identifiable as the small orange spot in the false-colour overlay. Sufficient feature contrast was found to exist between video frames from the TIR camera so as to permit stitching together of the infrared mosaic image and thereby maintain exposure consistency between constituent frames. The process is scalable and can be extended in order to construct a large mosaic of an extended area, particularly applicable in the opencut context in which leases are sizeable.

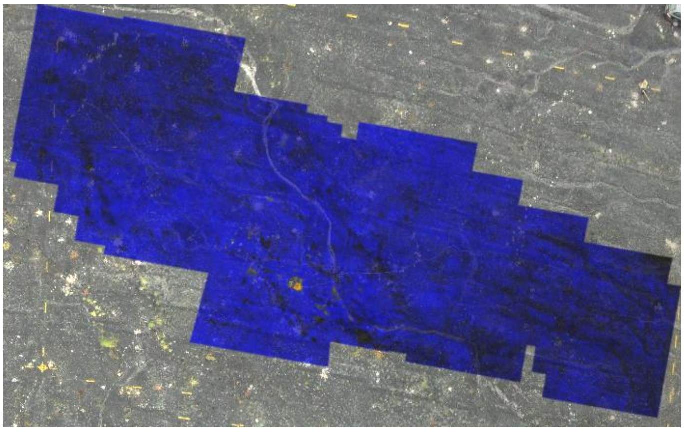

Figure 4 - TIR and visible-band mosaic created solely from image features of the composite images

The system was trialled at a third decommissioned site where surface heatings were ongoing and extended over a larger area. The flight plan shown in Figure 2 was executed and individual images from the TIR and visible-band video frames were retrieved. Since the UAS has the facility for recording flight data during a mission, it is therefore possible to determine the camera attitude orientation in space (azimuth, pitch and roll) as well as the geodetic position and height (latitude, longitude, altitude), which in turn allows the individual frames to be registered within geographical information systems. Figure 5 shows the image and flight path data imported into GoogleEarth, with which it is possible to present the collection of perspective-corrected imaging results in their approximate position and orientation, and with reference to the executed flight plan, shortly after the flight. This facility is easily adaptable to enable this mode of presentation to be generated in real time as the flight progresses.

Subsequent to data acquisition, the TIR and visible-band video sequences were processed, selecting individual frames from each to respectively include in single TIR and visible-band mosaic images. The resulting large image (5653 x 5740) is down-scaled for presentation and shown in Figure 6. As in Figure 3, the yellow and orange regions represent temperatures in the range of roughly 60^{o}C through to 200^{o}C, whereas the blue regions are of order 20^{o}C to 30^{o}C. Using these images, a comprehensive assessment of the full extent of the heatings can be readily discerned. Subsequent trials are planned in order to assess any time-evolution of the heating. Once again, due to the facilities available with the UAS, the same flight path can be re-flown and the resulting mosaics directly compared in order to easily and effectively track the progress of heating.

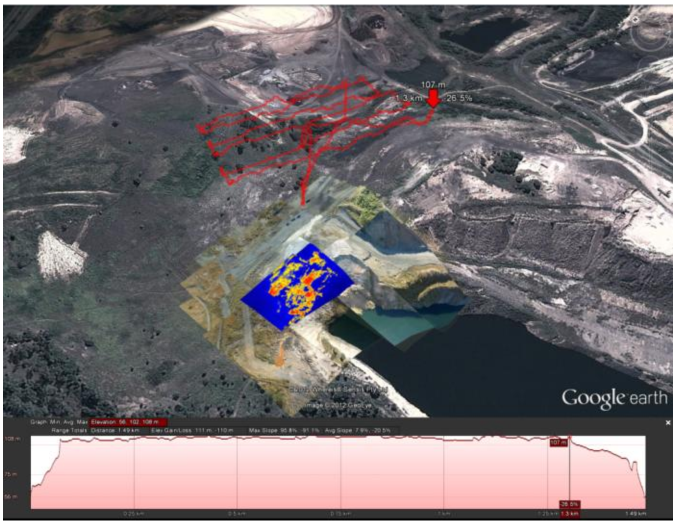

Figure 5 - Mission flight path data imported into the GoogleEarth geographical information program. The red curve is the 3D position recorded by the onboard navigation and control systems of the Unmanned Arial Vehicle (UAV). Also shown (bottom inset) is the altitude series as a function of flight path distance (in kilometres). Individual image frames from the TIR and visible-band video sequences are keystone-corrected and overlaid on the GE terrain using information derived from the UAV attitude and position at the time each image was recorded.

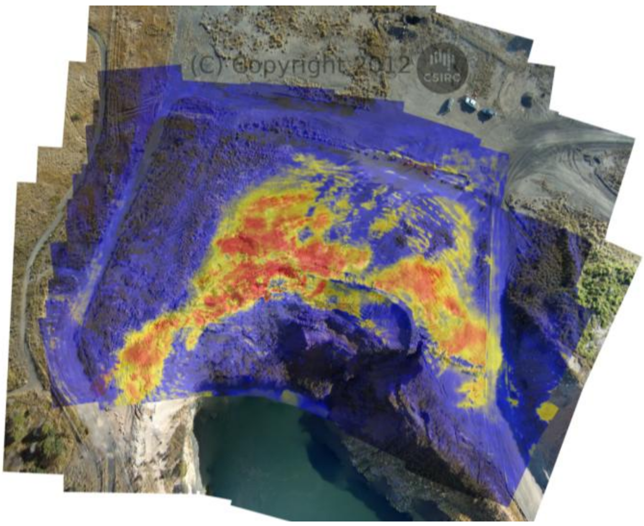

Figure 6 - TIR and visible-band mosaic of survey region exhibiting extended surface and sub-surface heatings

In addition to production of image mosaics, the quality of data obtained from the prototype system permits the retrieval of 3D information of the surface via photogrammetric principles and those employed in structure-from-motion techniques. Figure 7 shows a further trial of a heatings-prone excavation in which TIR and visible-band mosaics were similarly constructed as in Figure 6. Software applications were then employed to retrieve the 3D information from the image sets and generate a 3D mesh of points representing the inferred geometry of the imaged surface. The combination of the 3D mesh and the high-resolution mosaic imagery permits the construction of the 3D models shown, and in which the position of heatings in the context of the surface relief can be made. Such capability creates numerous additional possibilities, such as being able to plan mitigation strategies in response to the accessibility of active heating, as well as for volumetric analyses that may help project the extent and depth of areas of surface expression.

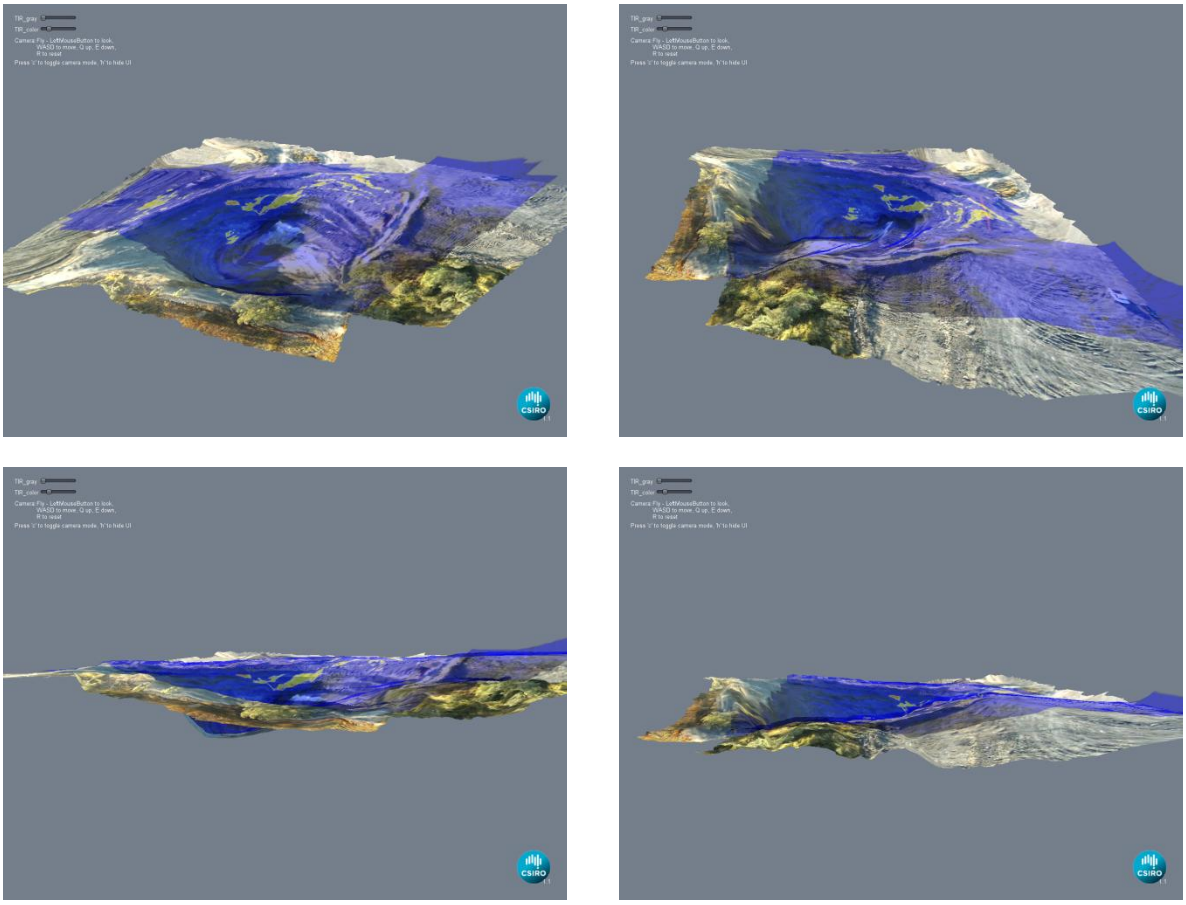

Figure 7 - Four different view of a model constructed from the 3D information present within the TIR and visible-band video frames

CONCLUSIONS

The advent of commercially accessible unmanned aerial systems in combination with lightweight thermal infrared and visible-band imaging systems has permitted the development of a new capability in management of coal-related surface heatings in the opencut context. In particular, the aspects of low-cost, high-flexibility and convenience, and the wealth of spatial and temporal information that can be obtained from this straightforward imaging measurement, makes this approach immediately suitable for employing in sponcom-related management and for defining new standards of practice in the industry.

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