EVALUATION OF TEMPERATURE IN A SELF-BURNING COAL WASTE PILE CONSIDERING UAV DATA AND IN SITU MEASUREMENTS

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ABSTRACT

The São Pedro da Cova (Portugal) coal mine produced a significant volume of waste deposited in different piles that have been on self-burning, continuously, for the past 15 years, increasing regional environmental concerns. Attempting to study and monitor the combustion phenomenon in these waste deposits, periodic measurements have been made using multiple sensors on-board of an unmanned aerial vehicle (UAV) and also *in situ* measurements. Assessments from RGB camera, thermal infrared and multispectral sensors, in addition to the geostatistical analysis of the *in situ* data, confirmed that the self-burning process is still active. Furthermore, the UAV methodology applied seems adequate for steep settings with difficult accessibility, as well as allowing for a better understanding and monitoring of the overall progression and state of the waste piles' self-burning process.

Index Terms— Coal Mine, Self-burning, UAV, *Kriging*, Thermal Infrared

1. INTRODUCTION

The São Pedro da Cova coal mine (Gondomar, Portugal) was exploited between 1795 and 1972, having produced as part of its environmental legacy a waste pile of about 28,000 m^2, which has been undergoing continuous self-combustion since 2005. Self-burning coal waste piles can be responsible for the mobilization of pollutants, which can be disseminated through the adjacent air and water table [1, 2]. The São Pedro da Cova coal mine is located, approximately 10 km east of Porto, Portugal, near the population center of São Pedro da Cova and is contiguous to multiple social infrastructures. Therefore, it is of vital importance to monitor the activity levels within the waste pile, in order to assess the current and potential risks posed to the inhabitants and propose adequate mitigation measures [3]. In order to better understand and monitor the spatial extent of the self-burning process, several measurements of the surface temperature were performed considering several types of sensors on-board of an UAV, as well as *in situ* spot temperature quantifications with the use of a thermal infrared thermometer.

2. METHODS AND EQUIPMENT

2.1. Methods

Two campaigns of UAV flights were concluded (one campaign on the 23rd July 2019 and another on the 30th December 2019), within which three flights were done. Each flight carried a different sensor, specifically, a thermal infrared (TIR) sensor, an RGB camera and a multispectral sensor (blue, green, red, red edge and near infrared bands). During the first campaign (23rd July 2019), the air temperature varied between 16ºC - 20ºC. In the second campaign (30th December 2019), the air temperature varied between 6ºC - 17ºC high. The specifications for these two flights are presented in Table 1.

Table 1 - Detailed characteristics of the flights and data acquisitions.

	UAV Altitude (m)	Longitudinal overlay (%)	Lateral overlay (%)
TIR sensor	100	75	75
RGB camera	150	70	70
Multispectral sensor	140	75	75

For the *in situ* measurements, a global navigation satellite system (GNSS) receiver and a TIR thermometer were used and 55 points were measured. These data were obtained on the 4th of December 2019, where the air temperature varied between 5ºC-14ºC. Subsequently, a geostatistical analysis of the *in situ* data was performed using the *ordinary kriging* method in order to create a continuous surface temperature map of the waste pile [4].

2.2. Equipment

An UAV Phantom 4 Pro was used in the flights campaigns. The TIR sensor used for the acquisition of thermic data was the FLIR Systems' Vue Pro R. The multispectral sensor used

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was the *Micasense RedEdge*. The specifications regarding these sensors' characteristics are described in Table 2.

Table 2 - Detailed specifications for the multiple sensors used during the campaigns.

	RGB camera	TIR sensor	Multispectral sensor
Resolution (MP)	20	0.33	1.2
Image size (in pixels)	5472 by 3648	640 by 512	1280 by 960
Sensor pixel size (mm)	0.0026	0.017	0.00375
Sensor size (mm)	12.8 by 7.2	10.9 by 8.7	4.8 by 3.6
Focal length (mm)	8.8	13	6
Spectral Band (μm)	0.4-0.7	7.5 to 13.5	(see table 3)
Sensor weight (g)	No data	113	180

The *Micasense RedEdge* multispectral sensor records data in five different bands, as presented in Table 3.

Table 3 - *Micasense RedEdge* bands description.

Band number	Name	Central wavelength (nm)	Wavelength bandwidth (nm)
1	Blue	475	20
2	Green	560	20
3	Red	668	10
4	Near infrared	840	40
5	Red edge	717	10

During the process of *in situ* data acquisition, a TIR thermometer (Electronic temperature instruments Ltd. RayTemp 4) measured the superficial spot temperatures in specific points. Simultaneously, the GNSS Trimble R6 receiver was used to determine the geographical coordinates of these points. The TIR thermometer features a 9:1 lens and a fixed emissivity of 0.95. The measurements using the TIR thermometer were taken around 45 centimetres above the target point, resulting in a surface incidence 5 centimetres across.

3. RESULTS

The UAV data was processed in order to create a georeferenced continuous image of the acquired data (orthomosaic). Due to the area covered by the UAV campaigns exceeding the region of interest, the orthomosaic was limited to the extent of the area occupied by the waste pile. Fig. 1 presents the RGB orthomosaics obtained in the two UAV campaigns.

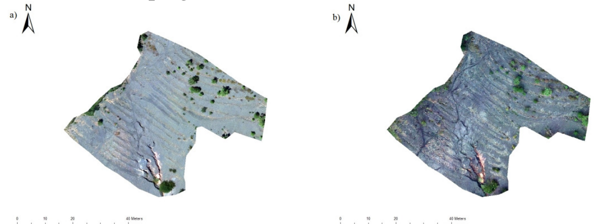

Fig. 1 - a) Orthomosaic considering RGB data of the 23rd July 2019 flight; b) Orthomosaic considering RGB data of the 30th December 2019 flight.

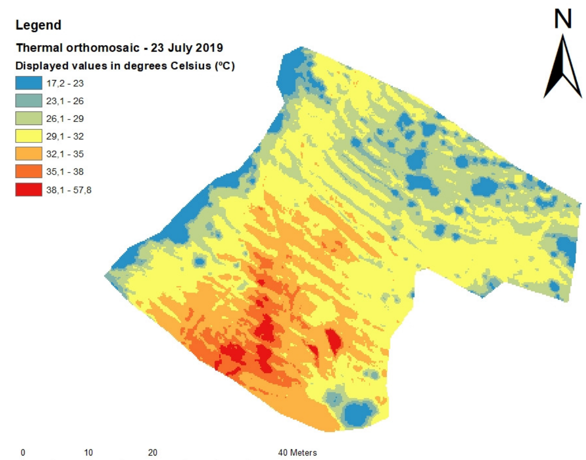

Fig. 2 - Thermal orthomosaic acquired in the flight of the 23rd July 2019.

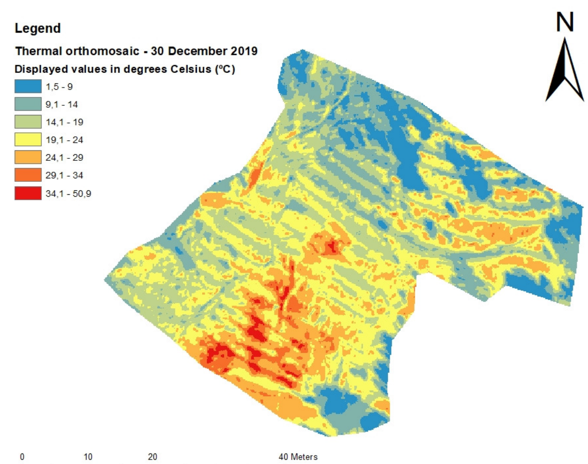

Fig. 3 - Thermal orthomosaic of the flight conducted on the 30th December 2019.

The same processing methods were then applied to the thermal data acquired by the TIR sensor on-board of the UAV. The resulting thermal orthomosaics are shown in Fig. 2 and 3.
Considering the *in situ* measurements, a geostatistical approach using the *ordinary kriging* method was employed, in order to create a continuous surface temperature of the waste pile. Fig. 4 shows the map obtained.

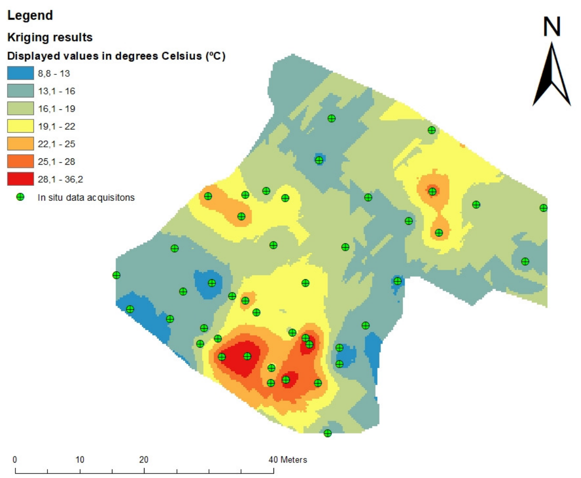

Fig. 4 - Interpolated surface temperatures considering the *kriging* method. The green dots correspond to the *in situ* measurements.

As a stochastic method of interpolation, the *kriging* method has associated errors. In this case, it was verified a mean error of 0.618, a root mean square error (RMS) of 6.28, a root mean square standardized error of 0.868 and an average standard error of 7.22.
Subsequently, an assessment of the statistical characteristics of the displayed thermal data is of interest. Therefore, a statistical analysis of both thermal orthomosaics and temperatures derived from the *kriging* model are shown in Table 4. The verified temperature differences between the collected data are mainly due to the different dates of data acquisition. Therefore, the air temperatures at the time of the acquisition has a direct influence in the results obtained.

Table 4 - Statistics associated to acquired thermal data.

	First flight	Second flight	*Kriging*
Minimum (ºC)	17.19	1.51	8.84
Maximum (ºC)	57.78	50.91	36.22
Mean (ºC)	29.79	18.36	17.83
Standard deviation (ºC)	3.91	6.59	3.58

Additionally, the analysis of slope and aspect is important for the understanding of the areas' accessibility and solar exposure (Fig. 5).

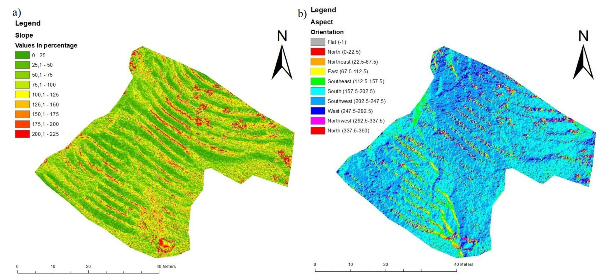

Fig. 5 – a) Slope and; b) Aspect, for the study area.

A statistical analysis of the slope and aspect were performed (Table 5).

Table 5 – Statistics from the slope and aspect data.

	Slope (%)	Aspect (º)
Minimum	0.05	Not applicable
Maximum	2870.18	Not applicable
Mean	76.99	200.40 (South)
Standard deviation	68.15	49.58

The multispectral sensor data allowed for further analysis of the study area, namely, the presence and growth of vegetation. Therefore, was computed the normalized difference vegetation index (NDVI) [5] and the enhanced vegetation index (EVI) [6] were estimated, in addition to the assessment of the proportion of vegetation and soil present in the waste pile surface (K-Means cluster unsupervised classification) [7]. The results are shown in Fig. 6.

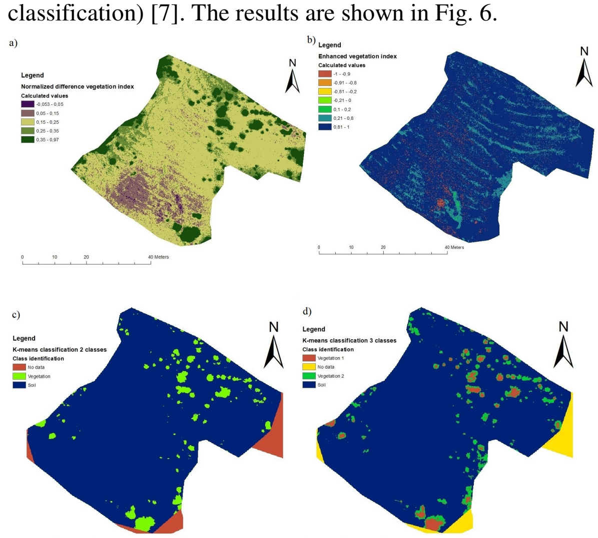

Fig. 6 – a) NDVI map; b) EVI map; c) K-Means classification considering two classes; d) K-Means classification considering three classes.

The proportions of soil and vegetation, considering the K-Means cluster analysis were 94.9% and 5.1%, respectively. Considering three classes, the proportions were 92.49%, 2.4% and 5.11% for soil, vegetation class 1 and vegetation class 2, respectively.

4. DISCUSSION

The coal waste pile shows high surface temperatures for the period analysed. Despite the fact that the waste pile is facing a southerly direction, receiving direct sunlight for most of the morning and part of the afternoon, the high temperatures cannot be attributed to the heat dispersed on the surface by the sun due to the similar results garnered by both flights. The first campaign was done during the high solar radiation output of summer and the second campaign during low solar energy in winter. Similarly, the *in situ* measured temperatures cannot be explained by air temperatures, owing to the significantly lower air temperatures measured during both TIR sensor flights, especially when compared to the surface hot spots.

Moreover, the use of the UAV for the purposes of assessment and monitoring proved invaluable due to the topographic nature of the region of interest (extremely high slopes), which makes in situ measurements arduous. This integrated approach could be used in similar terrain conditions. Additionally, there's a noticeable correlation between the highest spot temperature measurements and the hot spots detected by the TIR sensor.

Furthermore, it is noted that the area occupied by the coal waste pile with temperatures above 30 ºC presents no vegetation. Despite this, there is some sparse vegetation present in areas with temperatures below 30 ºC.

Regarding the interpolated surface temperatures, there is some correlation, in most of the areas, between this data and the measurements of the TIR sensor, despite the RMS error of the *kriging* model obtained. More *in situ* measurements need to be performed and more interpolation methods should also be tested [8].

5. CONCLUSION

The surface temperatures estimated remotely by the UAV sensor are confirmed by the *in situ* measurements, despite an appropriate cross validation not yet being performed.

The lack of vegetation, or its healthy growth, are explained by the high temperature values existent in the region, incompatible with the presence of dense vegetation. The RMS error related to the interpolated model could be explained by the poor spatial correlation between the measured temperature points. Nevertheless, the process of *in situ* data acquisition will also be used as a method of cross validation for the measurements of the TIR sensor. Since this project is still ongoing, the continuing monitorization and analysis of the coal waste pile, with future data gathering might provide insights to the development trends of the area as well as shine a light in previously undisclosed matters. It should also be mentioned that the monitoring of this waste pile also involves water and soils quality analysis. This work presents a new and an integrate approach that combines remote sensing measures considering different sensors and in situ measurements. Moreover, the combination of all techniques applied allowed to take important conclusions regarding the waste pile combustion process, which is crucial for the management of the surrounding environment.

6. ACKNOWLEDGMENT

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