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ABSTRACT

Airborne thermal infrared (TIR) imaging systems are being increasingly used for wildfire tactical monitoring since they show important advantages over spaceborne platforms and visible sensors while becoming much more affordable and much lighter than multispectral cameras. However, the analysis of aerial TIR images entails a number of difficulties which have thus far prevented monitoring tasks from being totally automated. One of these issues that needs to be addressed is the appearance of flame projections during the geo-correction of off-nadir images. Filtering these flames is essential in order to accurately estimate the geographical location of the fuel burning interface. Therefore, we present a methodology which allows the automatic localisation of the active fire contour free of flame projections. The actively burning area is detected in TIR georeferenced images through a combination of intensity thresholding techniques, morphological processing and active contours. Subsequently, flame projections are filtered out by the temporal frequency analysis of the appropriate contour descriptors. The proposed algorithm was tested on footages acquired during three large-scale field experimental burns. Results suggest this methodology may be suitable to automatise the acquisition of quantitative data about the fire evolution. As future work, a revision of the low-pass filter implemented for the temporal analysis (currently a median filter) was recommended. The availability of up-to-date information about the fire state would improve situational awareness during an emergency response and may be used to calibrate data-driven simulators capable of emitting short-term accurate forecasts of the subsequent fire evolution.

Keywords: Wildland fire, automatic tracking, aerial surveillance, thermal infrared, rate of spread, active contours, video fire analysis

1. INTRODUCTION

Remote sensing may play a crucial role if used to obtain relevant time-critical information during a high-risk event such as a forest fire. An efficient fire emergency response is highly important to minimise ecological and economic losses once a fire event has started. Despite public agencies' preventive efforts, the number of fires and the annually burned area have been increasing in the past years.[1–3] Moreover, some authors have forecasted a further rise in fire seasons' length and severity for the near future.[4–6]

In the event of a wildland fire, situational awareness is of the utmost importance to guarantee the safety of emergency responders and boost the efficacy of suppression jobs. Furthermore, being able to accurately determine the geographical location of the fuel burning interface and its rate of spread could be helpful to calibrate a number of data-driven fire spread simulators.[7–11] If the fire evolution can be tracked in real time, these simulators may be able to emit quick forecasts of the subsequent fire development based on the observed dynamics.

Owing to the intrinsic danger related to a forest fire scenario, fire spread observations are difficult to be performed on the ground. On the contrary, remote sensing technologies present a great potential in this field, and several systems are currently devoted to wildland fires. Spaceborne sensors have been used in the past decades for tasks such as early fire detection, remote measurement of burned areas and estimation of carbon dioxide emissions.[12] However, they show too coarse spatio-temporal resolutions to be suitable for active fire

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tracking. Aerial imagery, which does not have these drawbacks, has also been deployed for tactical surveillance purposes.[13–16] Nevertheless, the information provided by these systems is assessed only qualitatively and, to the best of our knowledge, no automatic image analysis algorithms have been published so far except for our previous works.[17] When required, fire perimeters are annotated manually.[18–23]

This article presents a video fire analysis algorithm designed to automatically locate the contour of an active wildland fire. Whereas the detection of the unburned-burning fuel interface is rather uncomplicated in regions without intense flaming, difficulties arise when the fire base is to be distinguished from flickering flames. These flames, which can be several dozen meters in length, become distorted during the 2D projective transformation which is commonly used for image georeferencing when ground control points are available. As a result, a series of finger-like shapes appear aligned with the direction of the camera viewpoint. In order to filter out these flame projections, we developed the methodology described in Section 2 and we tested it in three experimental large-scale scenarios as exposed in Section 3. Following the analysis of results, the most relevant concluding remarks and suggestions for future work are included in Section 4.

2. METHODOLOGY

The approach adopted to filter out flames and detect the spatial limits of an active wildfire consists in the computation of a fire mask including all hot zones followed by a temporal analysis for the removal of rapidly varying areas. Firstly, the fire contour is computed in each frame without distinguishing which parts of this contour correspond to the actual fire base and which represent flames. Secondly, the temporal analysis determines which zones present high-frequency variations and associates them with the presence of flames. The previously detected fire contour is consequently smoothed in these areas so that flames are removed from the output contours.

Initial fire contour detection is performed by means of active contours without edges.[24] This pproach presents a more general formulation than classical active contours. Active contours are curves designed to evolve within an image following the action of internal and external forces until they find the position of minimum energy[*]. In other words, the optimum object recognition in an image is achieved through the minimisation of an energy-based segmentation (Eq. 1):

$$inf_{c_1,c_2,C}\ F(c_1,c_2,C) \tag{1}$$

where $F(c_1,c_2,C)$ is the energy functional defined by Eq. 2:

$$\begin{aligned} F(c_1,c_2,C) = \mu \cdot Length(C) + \nu \cdot Area(inside(C)) + \lambda_1 \int_{inside(C)} |u_0(x,y) - c_1|^2 dxdy \\ +\lambda_2 \int_{outside(C)} |u_0(x,y) - c_2|^2 dxdy \end{aligned} \tag{2}$$

$\nu \geq 0, \nu \geq 0, \lambda_1, \lambda_2 > 0$ are fixed parameters, u_0 is the given image, C is the variable curve and the constants c_1, c_2 are the averages of u_0 inside and outside C, respectively.

In this case, the values $\nu = \mu = 0$ and $\lambda_1 = \lambda_2 = 1$ were selected following recommendations given in Ref 24. In addition, the optimisation problem must be initialised with a curve location from which it is to evolve towards the energy minimum. In this study, the initial curve coordinates are obtained through intensity thresholding. A threshold of $T = 450K$ is applied to distinguish fire and smoke from the cold background. Simple intensity thresholding is not robust enough to be used as stand-alone fire contour detection because it is affected by hot smoke located close to the flames. However, this technique may be employed to obtain a first fire-contour guess which is sufficiently close to the actual shape and can be subsequently refined through an active contour. The threshold is set to $T = 450K$ in order to include all fire-related pixels in the foreground mask. A higher threshold would exclude pixels corresponding to areas burned some minutes ago, whereas a lower threshold might include

[*]The energy defined here relates only to the image properties and has no direct physical meaning.

cold background objects in the fire mask. Following intensity thresholding, morphological closing and filling operations are performed.

For the time analysis, fire contours are described by means of their Contour-Centroid Distance (CCD). The CCD distribution is a 1-D contour descriptor computed as the distance from each contour point to the centroid of the silhouette.[25] In the present algorithm, similarly to Ref. 26, a polar formulation was chosen and discretised over 128 equally spaced intervals. Subsequently, these 1-D CCD polar distributions are piled in the time dimension and a 1-D median filter is applied to remove high-frequency variations. Flame flickering behaviour has been acknowledged in the literature to be a wide-band activity covering frequencies from 1 to 13 Hz.[27] Such values are in accordance with the flickering frequency observed in the experimental footages described in Section 3, which was estimated in approximately 1 Hz. Therefore, considering the analysed footages exhibit a frame rate of 4 fps, the median filter was implemented with order 15 so that the temporal variation of each contour point is analysed in a window of around 4 s.

3. PRELIMINARY RESULTS

The methodology described in Section 2 was tested over a set of TIR footages acquired during an experimental campaign in the Ngarkat Conservation Park, South Australia.[28,29] Prescribed burns were performed in flat mallee and heath shrubland plots with areas between 4 and 25 ha. Fire spread was recorded off-nadir from a hovering helicopter. A TIR camera with the properties shown in Table 1 was operated manually by the onboard crew. Footages corresponding to three of these experiments, from which sample frames are displayed in Figure 1, were georeferenced using a direct linear transformation[30] as in previous similar studies.[19,31] The set of ground control points used for this purpose consisted of fire beacons placed next to the plots whose coordinates had been measured using differential GPS devices.

Frames displayed in Figure 1 exemplify how flames became distorted during the geocorrection step. Their apparent length was considerably increased as a result of the 2-D projective transformation, resulting in unrealistic finger-like shapes orientated in the direction of the oblique camera view. These shapes do not resemble the real flames and must be filtered out so that the actual fire perimeter can be accurately located. Figure 2 shows the fire contours obtained over a video sequence with appreciable flames as well as their corresponding CCD distributions.

For the temporal analysis, CCD distributions were piled in the time dimension to create a 3D surface such as those displayed in Figure 3. Subsequently, 1-D median filtering was applied to remove high-frequency temporal oscillations caused by flame projections. Filtered CCD evolutions for the three analysed footages are shown in Figure 4.

After filtering high-frequency variations assumed to correspond to flames, smooth fire contours were reconstructed from smooth CCD distributions. Figure 5 shows the results for the sample frame sequence presented in Figure 2.

Table 1. Technical specifications of the employed thermal camera.

Commercial name	FLIR AGEMA Thermovision 570-Pro
Detector type	FPA (focal plane array)
Temperature measurement range	$-20\ to\ 1500\ °C$
Precision	$\pm 2\%$
Thermal sensitivity	$< 0.15\ °C$
Field of view	$24°\ x\ 18°$
Spectral range	$7.5 - 13\ \mu m$
Spatial resolution	240 x 320 pixels
Temporal resolution	5 fps

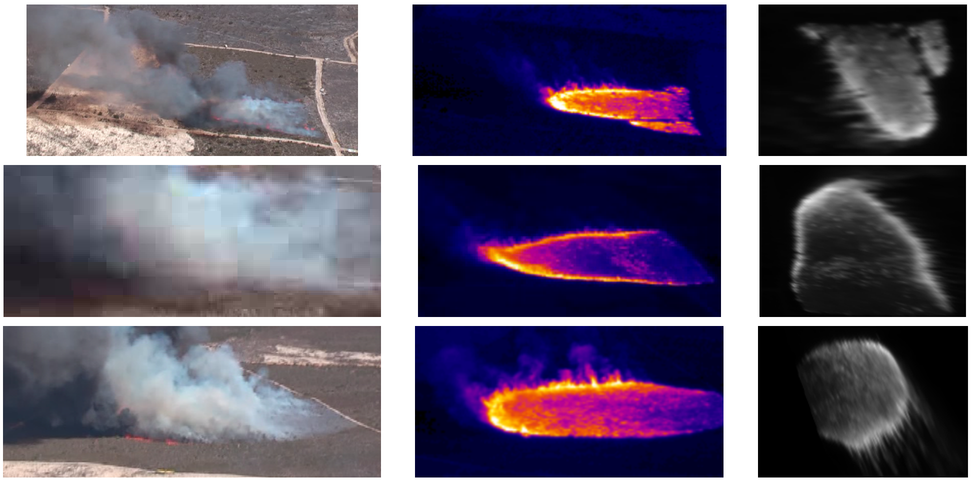

Figure 1. Sample frames from three large-scale experimental burns. Left: visible spectrum. Middle: raw off-nadir frames in the TIR spectrum. Right: georeferenced TIR frames with the north upwards. Top: test 1; middle: test 2; bottom: test 3.

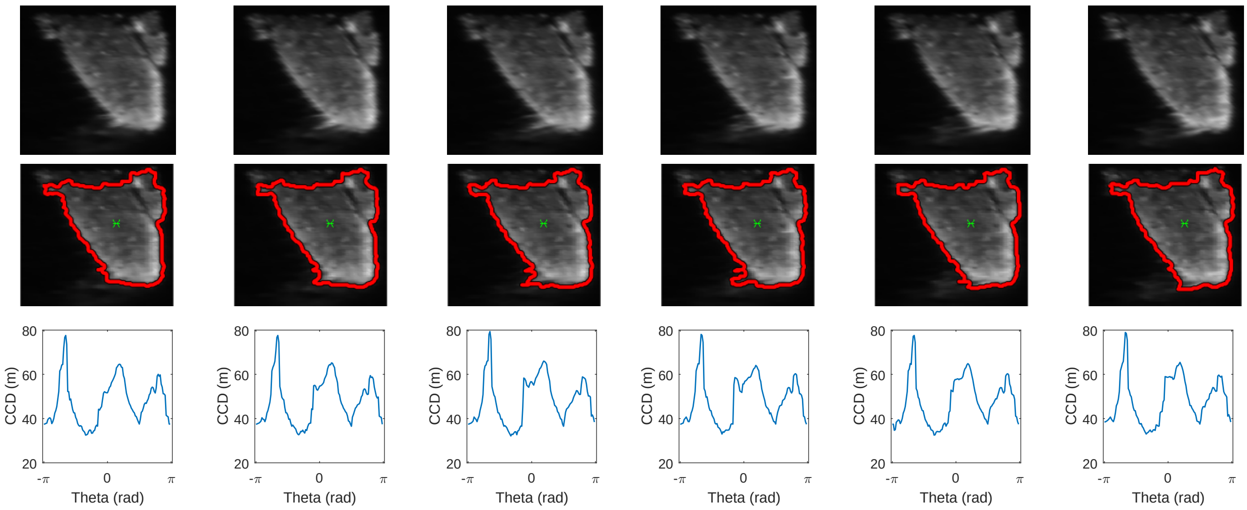

Figure 2. Sample sequence from test 1, composed of six consecutive frames acquired at a rate of 4 fps. Top: georeferenced TIR frames. Middle: detected fire contours. Region centroids are displayed in green. Bottom: Contour-Centroid Distance distribution of the fire contours.

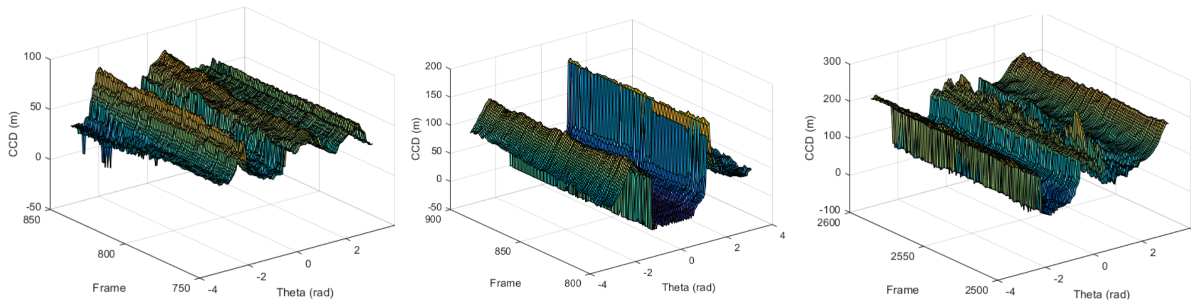

Figure 3. Temporal evolution of the fire Contour-Centroid Distribution for a 25 s-section of the three available experimental footages. Left: test 1; middle: test 2; right: test 3.

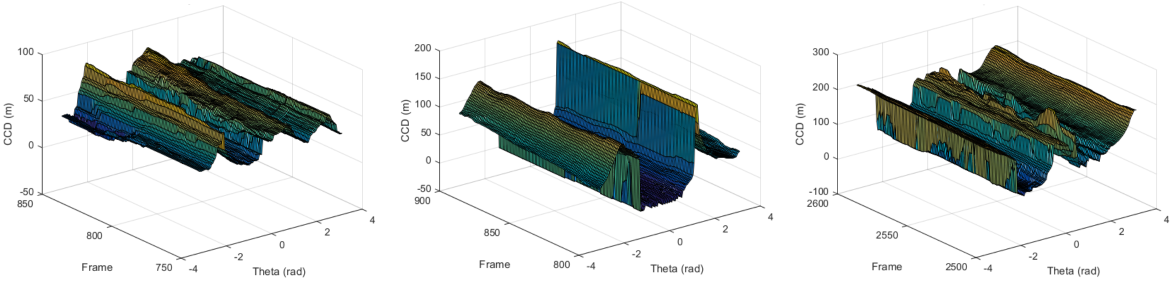

Figure 4. Temporal evolution of the fire Contour-Centroid Distribution for a 25 s-section of the three available experimental footages, after 1-D median filtering. Left: test 1; middle: test 2; right: test 3.

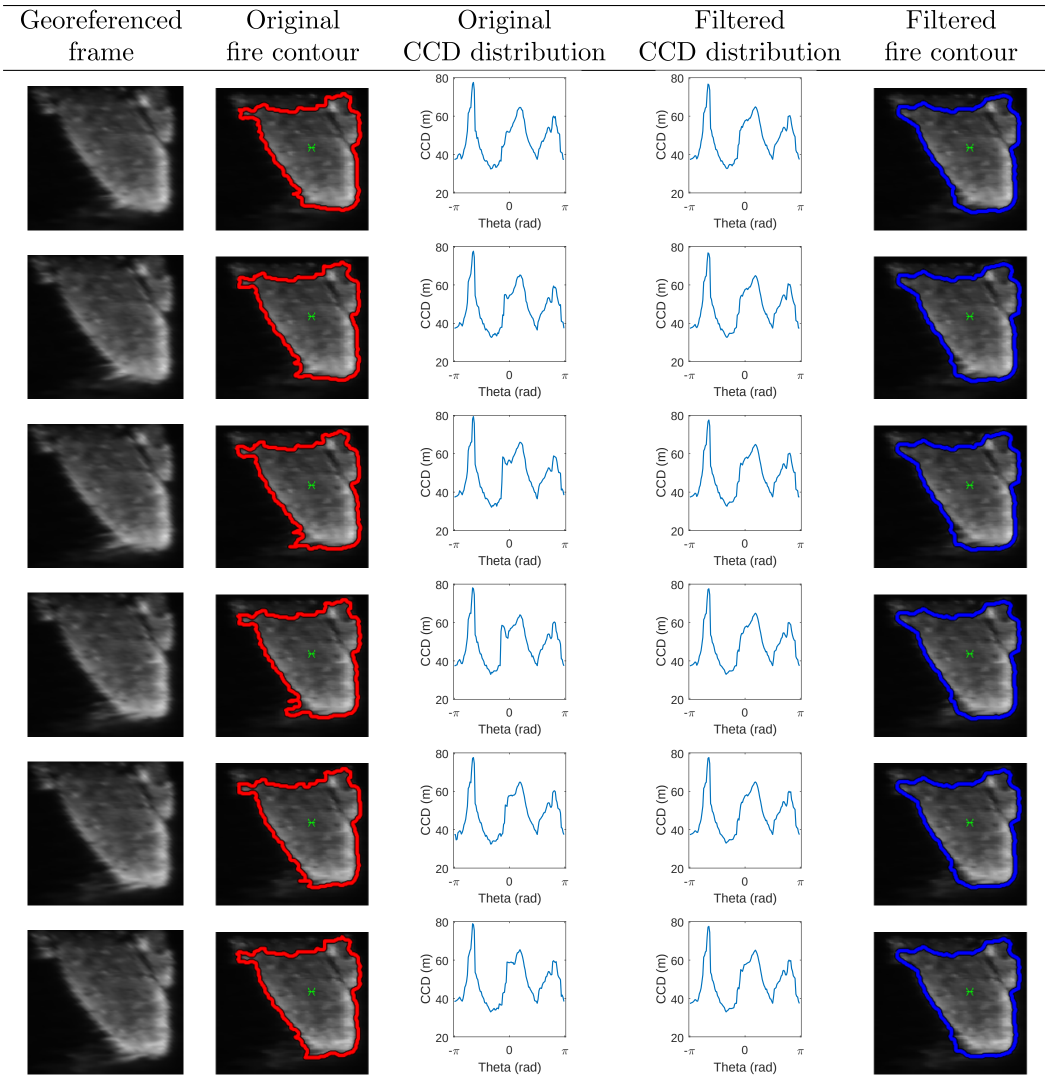

Figure 5. Results for the sample sequence from test 1 presented in Fig. 2.

As exemplified in Figure 5, flames were correctly filtered by the proposed algorithm. Similar results were obtained for other video sequences from the three available experiments. However, the resulting fire contour was not always attached to the actual fire base but was in some cases displaced in the direction of flames. The sequence displayed in Figure 5 corresponds to one of these cases. This offset appeared when applying median filtering through a sequence where the majority of the frames were affected by flames. In these cases, median values, although robuster to noise than average values, may also become biased. An appropriate adjustment of the filter order allowed reducing the impact of this phenomenon, but the optimum order value could not be easily estimated a priori. Therefore, either a methodology to automatically estimate this optimum order is needed or different filtering strategies should be explored.

4. CONCLUDING REMARKS

The present article intends to contribute towards the development of a wildfire tactical surveillance system based on remote sensing. An algorithm to automatically locate the fire contour of an active wildland fire in georeferenced thermal infrared imagery is presented, trying to fill the gap between airborne sensors deployed during wildfire emergencies and existing computer vision methods. One of the main difficulties to face before achieving the automated extraction of meaningful quantitative information about a forest fire is the filtration of flames. Flames must be distinguished from the fire base in order to locate the actual fuel burning interface. A combination of intensity thresholding, morphological processing, active contours and temporal analysis of contour descriptors is presented in this article to tackle this difficulty. The described methodology was tested on experimental data representative of a real operational scenario. Preliminary results were satisfactory, yet significant improvement opportunities were detected. Especially, an extended analysis of other possible low-pass filtering techniques is recommended since the current approach (median filtering) might not be robust enough when a high concentration of flames is present along several consecutive frames. Finally, the algorithm should be validated using a wider database of wildfire TIR images.

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