INSTRUMENTATION OF SPREADING FIRES: TOWARD THE DEVELOPMENT OF A METROLOGICAL SYSTEM BASED ON STEREOVISION

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Abstract
This paper presents research conducted in the area of stereovision in order to develop a metrological system for the measurement of geometrical characteristics of spreading fires. In the first part, the material and the algorithms used to obtain three dimensional coordinates of fire points are presented. The second part describes the stereovision framework used for laboratory experiments and the algorithms developed to estimate the fire front geometrical characteristics. With this system, a 3D global form of the fire is obtained at each acquisition time and the position of each point of the front, their rate of spread, their height, length, tilt angle, the width basis and the volume of the fire are estimated. In the third part, a stereovision framework developed for the geometrical characteristics measurement of fires at field scale is presented. Complementary information is obtained from different views of the fire. A Human Machine Interface gives the possibility to an expert to define from the lateral view the fire area to study. A three dimensional surface reconstruction of the back fire front is obtained and the height, the length, the position, the rate of spread, the tilt angle and the width of the front are estimated.

Introduction
In forest fire research, the experimental studies of the fire spread across vegetal fuels are of great interest for understanding and modeling the fire behavior. Parameters like the fire front geometrical properties (position, rate of spread (ROS), fire height, fire length, fire inclination angle, fire base width, surface, volume) are particularly interesting to compute during a spreading experiment because they influence the propagation and the heat transfer of the fire [1-4]. Visual and infrared cameras are now used as complementary metrological instruments in fire spread. Pastor *et al* [5] proposes a thermal image processing method for computing the ROS of linear fire fronts generated on flat surfaces with known dimensions. The authors use four calibration points located at the vertices of a rectangle plane with known side lengths. These points must be visible in the image during the experiments, which limits the approach to controlled environment experiments. Martinez-de Dios *et al* [6] have developed a system using visual and infrared images for laboratory fire spread analysis. The cameras are positioned at two view points (frontal and lateral views). This approach uses 2D information and cannot extract 3D depth information for all the points of a nonlinear fire front. Only the length of the most advanced point of the fire front and its inclination are estimated by the lateral view and the ROS is computed from the frontal view of the fire. Computer vision techniques are also applied to monitor forest fires in Martinez de Dios *et al* [7]. The system computes a 3D perception model of the fire. Multisensory fusion is conducted using telemetry sensors and GPS.

Fire modeling scientists need non-destructive systems in order to measure the geometrical characteristics of fire fronts in various scenarios: indoors on burn tables, and outdoors in unstructured environments at *meso* and field scales.

The aim of this paper is to present a research conducted using stereovision in order to develop a metrological system for the measurement of geometrical characteristics of spreading fires at laboratory scale and at field scale. In the first part, the material and the algorithms used to obtain three dimensional coordinates of fire points are presented. The second part describes the stereovision framework used for laboratory experiments and the algorithms developed to estimate the fire front geometrical characteristics. In the third part, a stereovision framework developed for the measurement of geometrical characteristics of fires at field scale and the experimental results are presented.

Stereovision material and 3D coordinates of fire points

Stereovision material

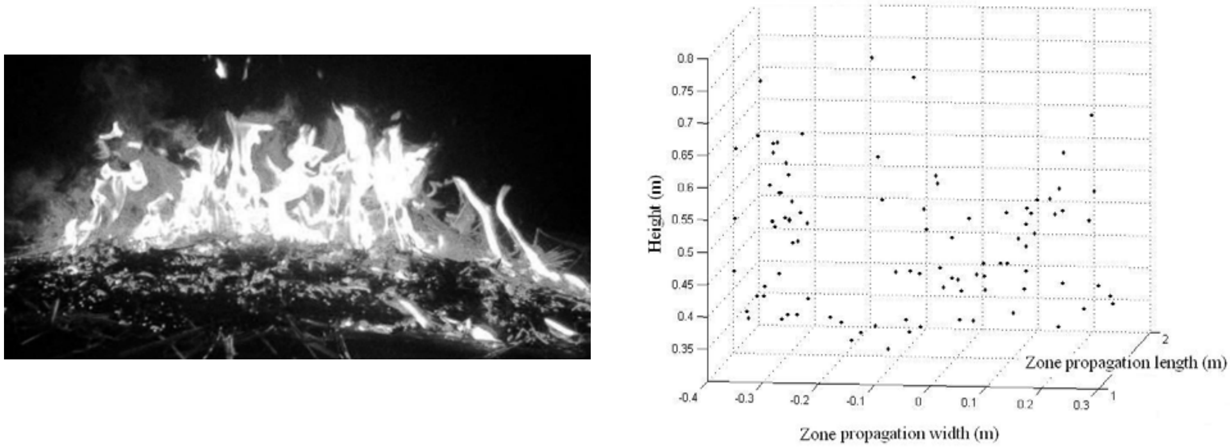
The basis material of the stereovision frameworks presented in this paper is a pre-calibrated multiple baseline stereo camera from Point Grey [8-9]. The camera is a color XB3 trinocular stereo system with a focal length of 3.8 mm, 66°HFOV (horizontal field of view), a 1/3” Sony ICX445AQ CCD with 1280×960 image resolution, a pixel size of 3.7 μm and a frame rate of 16 FPS. This system is accurately pre-calibrated for lens distortions and camera misalignments. The stereo pair, left and right images, is aligned to within 0.1 pixel RMS error. Also a calibration retention mechanism permits to minimize loss of calibration due to shock and vibration. Finally, the multiple baselines choice of 12 cm or 24 cm for stereo processing, make it possible to efficiently choose the best strategy for accuracy and occlusion handling. The precise pre-calibration of this optical system permits to avoid the calibration phase during the experiments. The three multiple baseline cameras are used in our experiments. For each acquisition, three images are captured and stored in RAW format. The three cameras are perfectly synchronized with a maximum synchronization time of 125 μs. Image acquisition code was developed and optimized using C++ programming language in order to attain real-time performance. Color interpolation and image rectification were done offline using a C++ program based on Triclops Stereo Vision SDK. In the developed rectification procedure, we process images by pairs. The images from the two distant cameras (24 cm baseline) form the first pair and images from the centre and right cameras (12 cm baseline) form the second pair. Since the baseline plays an important role in stereo accuracy [10], we considered the two distant cameras in most of the experiments (Considering all other parameters equal: the largest is the baseline, the better is the stereo accuracy). The use of the largest baseline permits to minimize the theoretical error along the Z axis during the three dimensional computation of the fire points.

Three dimensional coordinates of fire points

In order to compute the desired fire characteristics, the 3D coordinates of salient fire points are estimated using stereo image processing. The approach involves the following steps and is presented in [11]:

1. Segmentation of fire regions,
2. Extraction of salient feature points,
3. Automatic computation of stereo disparity over time,
4. Feature selection refinement using a normalized cross correlation matching strategy,
5. Computation of 3D fire points using stereo correspondence.

Figure 1 (*b*) shows the extracted 3D points of the fire front presented in fig. 1 (*a*) obtained from a multiple baseline stereo camera positioned in a back position relative to the propagation direction of the fire. The reference frame has its origin in the left image centre point of the back stereo camera.



(a) (*b*)

Figure 1. Frontal fire front image (*a*) and 3D fire points (*b*)

Stereovision framework for the geometrical characteristics estimation of laboratory fire propagations

Experiments of fire propagation were conducted at laboratory scale on a 2 m x 2 m platform that has been inclined up to 20°. The experimental system is composed of two stereovision cameras positioned respectively in a front position and in a back position of the fire propagation direction (fig. 2).

Figure 2. Stereovision cameras positioned in a front position and in a back position relative to the direction of the fire propagation

Estimation of the position, the rate of spread and the height of fire fronts

3D processing has been developed in order to estimate the evolution of the height, the position and the ROS of any point in a linear or nonlinear fire front. These characteristics are estimated over time directly from computed 3D fire points obtained from the back stereoscopic images. The details of this 3D processing are given in [11]. The main steps are:

1. *Estimation of the base plane and of the fire front lines*. As the fire is spreading along an inclinable table, the base of the fire is not at the same position over time. Therefore, it is necessary to differentiate between the points of the base plane and the points of the upper part of the fire front. The 3D points of the base of successive fronts are used to estimate the base plane of propagation with a least-squares technique. Each set of 3D points belonging to a fire front at a given time is projected on the base plane and a 2D front line is computed using a B-spline interpolation (fig. 3).
2. *Estimation of the rate of spread*. The ROS is estimated by considering the sets of pair-temporal successive front lines. Equidistant points are selected in the first front line. For each selected point of the first front line, a corresponding point on the second line is selected; it is the intersection of the normal at the selected point of the first front line and the second front line (fig. 3). For each point of the first line, its ROS is computed as the quotient of the distance between its position and its corresponding point on the second line and the lapse of time between the two image acquisitions corresponding to the two front lines.
3. *Estimation of the height of the fire front*. The 3D points of the fire front are projected in a plane with Y = 0 corresponding to the base plane of the front. The distance between the base plane and each point of the upper part of the fire corresponds to the height of the point. The projection of the 3D selected points on a fire front line is used for height estimation. The projection line (where the 3D data are projected) is divided into segments using a recursive algorithm. This algorithm divides each segment into sub-segments until one point per segment is obtained. The segment is then given the height of the point it contains. A B-spline interpolation is then applied to the points in the segments and used in order to obtain an estimation of the fire front height. The projection plane between the obtained segments and the 3D position permits the computation of local fire inclination. Figure 4 shows the estimated height of a fire front.

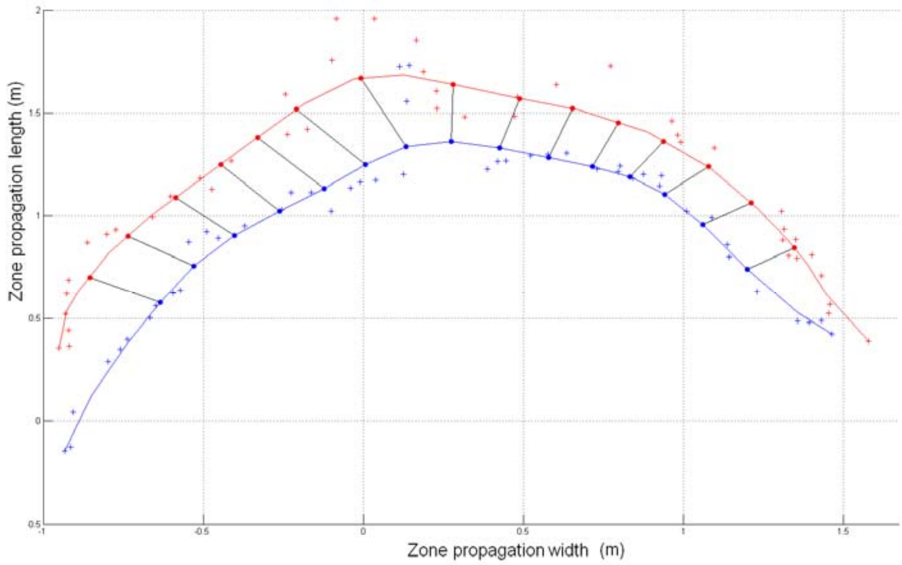


Figure 3. Fire front lines at two successive times

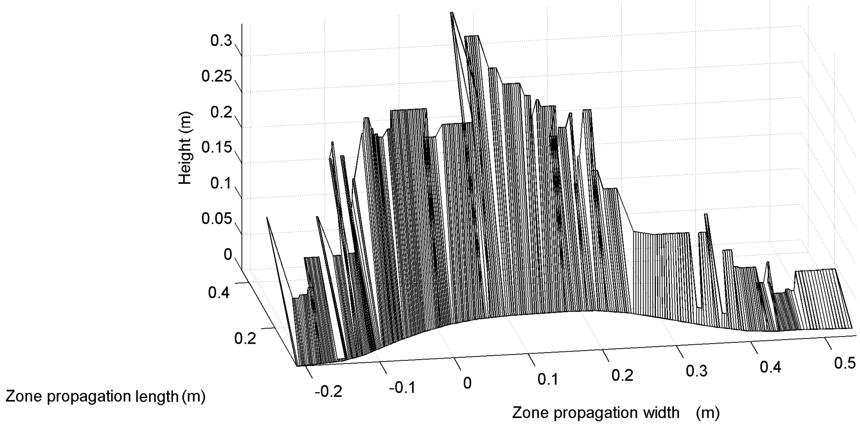


Figure 4. Height estimation of a nonlinear fire front

Estimation of the volume of the fire front

In order to estimate the volume of a fire front, it is necessary to compute a complete tridimensional form of the fire front. The 3D fire points obtained from the two synchronized stereovision cameras are complementary. They are projected in a same reference frame and used to build a global form of the fire front. The coordinate transformations of each system with respect to a single reference system are estimated using a registration procedure with a cube pattern. The details of this procedure are presented in [12].

Each set of 3D points (belonging to the back stereo camera images and front stereo camera images) is projected on the base plane and each of them is used to compute a 2D front line. Figure 5 shows the back line and the front line obtained from these two sets of 3D points. They correspond respectively to the position of the front and back of the fire front. The space between these two curves corresponds to the depth of the base of the fire front.

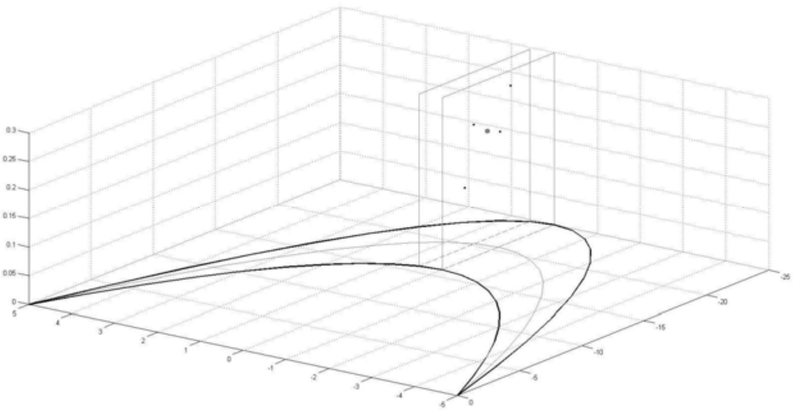


Figure 5. Base of the fire front and estimation of the height of the fire by slicing

From the front and back lines, a mean line is computed (line with grey color in fig. 5) and divided into regular intervals. The 3D points that are into the volume defined by the two perpendicular planes on the border of each interval are selected. These points are then used to compute a mean 3D point of each area (thick point in fig. 5) that is positioned on the mean curve. A three dimension meshing is then performed in order to estimate the three dimensional surface rendering. It is based on Delaunay triangulation and it produces a set of triangles as presented in [12]. Figure 6 shows the front (*a*) and back (*b*) view of a fire spreading on a combustion table with an inclination angle of 20°.

Figure 6. Front (*a*) and back (*b*) view of a fire

Figure 7 shows the 3D surface rendering of such fire.

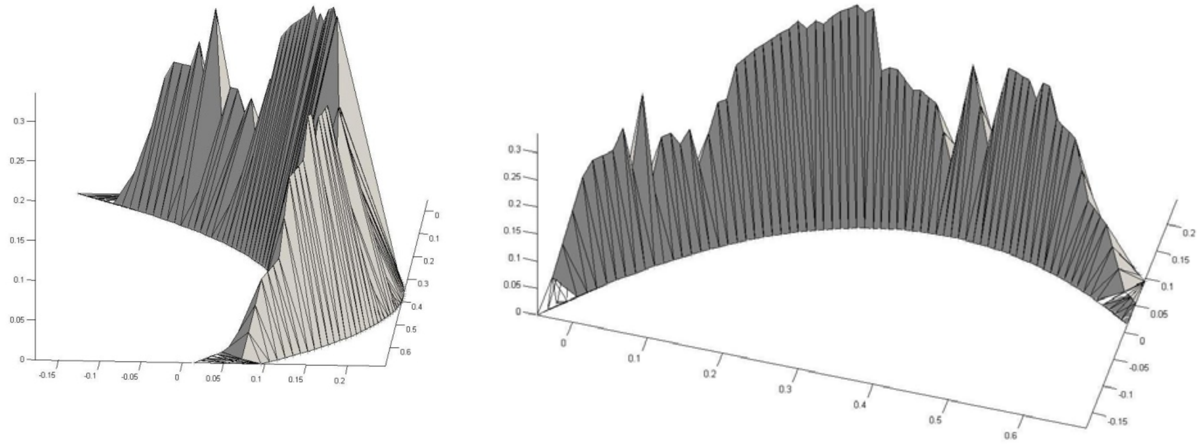


Figure 7. Global form of the fire presented in figure 6 (*b*)

The estimation of the volume is performed by the sum of the volume of 3 tetrahedrons for each triangle of the computed mesh.

Stereovision framework for the geometrical characteristics estimation of fire propagations at field scale

Critical points were considered for the development of the system dedicated to field experiments. First, generally, fires do not occur at the same location and the place can’t be chosen beforehand. Second, the dimension and the extent of the spread can be large. Taking into account these points, a portable vision system, electrically independent and relatively easy to deploy has been built. It is composed of the same cameras described previously and positioned respectively in a lateral position and in a back position of the fire propagation direction (fig. 8). Presence of smoke makes it ineffective the positioning of cameras visible in front of the fire.

Figure 8. Deployment of stereo cameras

Figure 9 shows two views obtained from cameras on the ground.

(a) *(b)*

Figure 9. Lateral view (a) and frontal view (*b*) on one field experiment carried out in Letia (France) in 2010

A procedure especially created for the registration of cameras at field scale has been developed. It is based on the use of an easy transportable feature put successively at several positions on the field and visible by the different stereovision systems. For each stereovision system, the 3D position of the centre of gravity of the feature put at different places is compared with a theoretical network of positions generated by computer and put at a given place in space. The place which minimises the distance between the 3D positions of the feature and the theoretical network of positions gives the real pose (translation and rotation) of the features in the camera frame. When the poses are estimated in the two camera frames (back and side), the registration of the two features (in one frame) gives the extrinsic parameters of the global system of cameras. The feature is a balloon of one meter in diameter wrapped in a red cloth to be easily segmented in the images. Figure 10 shows an example of one position of the balloon relative to the position of the circled stereo cameras.

Figure 10. Balloon used for the registration method

Human Machine Interface to specify lateral fire points

Lateral images are not easy to treat automatically due to the presence of smoke which can hide partially or completely the fire front and also because the fire front can have a complex form with several flames that have different inclination angle and length.

A Human Machine Interface has been developed in order to permit to experts to specify the part of the front they want to consider for the estimation of fire characteristics. The expert clicks on the presented image in order to indicate three points that correspond to the position of the less advanced point of the fire front, to the position of the most advanced point of the fire front and to the position of the highest point of the fire front. The order in which the user clicks the points does no matter because they are automatically identified by the algorithm based on their 2D coordinates. By clicking on the "Next" button, the expert can choose not to process an image (fig. 11).

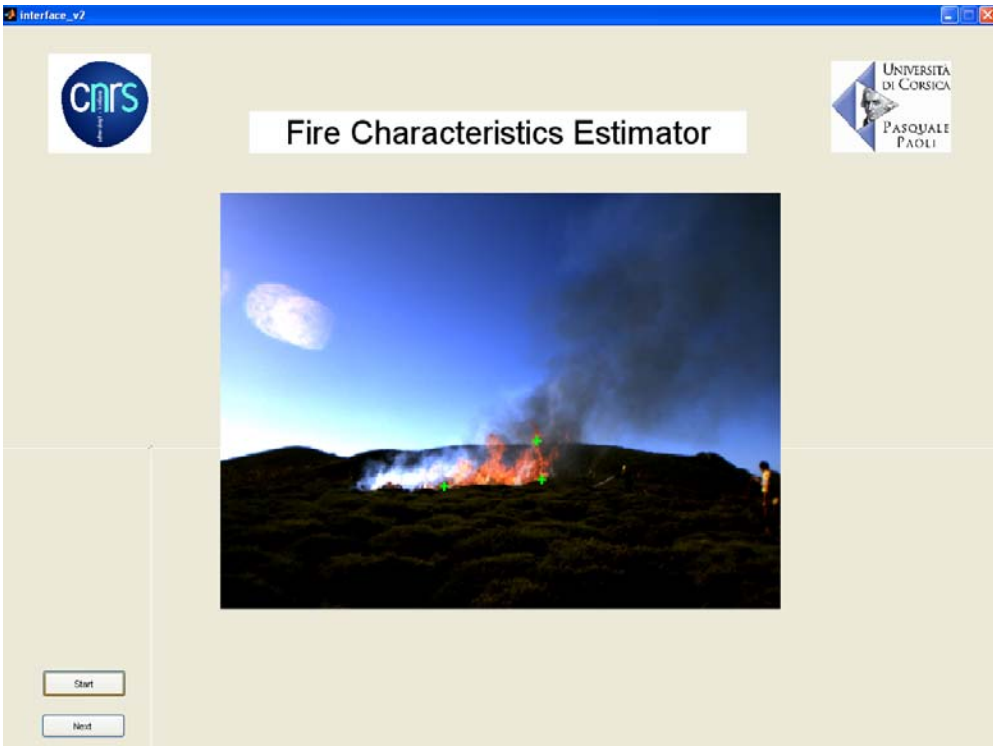


Figure 11. Selection of the fire area points

From these 2D points, their corresponding points are searched in the stereoscopic image and their 3D coordinates are computed. The highest 3D point is noted “A”, the less advanced 3D point is noted “B”, and the most advanced 3D point is noted “C”. Then, following the description of the parameters presented in fig. 12, the fire length, the fire front width, the position of the most advanced point with respect to a reference and the fire inclination angle are estimated

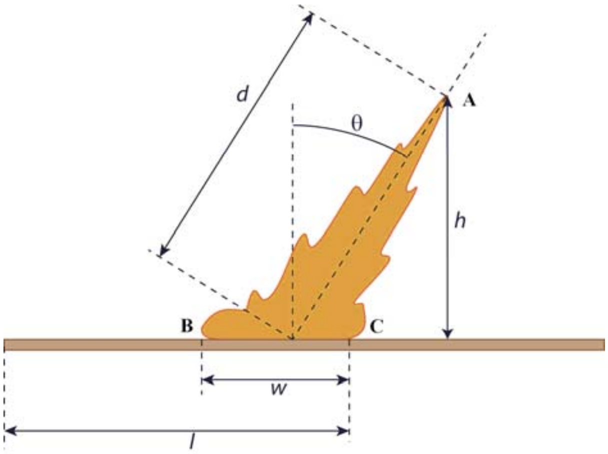


Figure 12. Description of the fire parameters to be measured: fire length (*d*), fire height (*h*), fire front width (*w*), position of the most advanced point with respect to a reference (*l*), fire inclination angle (ɵ)

Three dimensional surface reconstruction

A 3D surface reconstruction is computed from part of the points obtained with the back vision system and controlled by the 3D points obtained from the lateral vision system. All the points are merged in the same frame (the one of the back stereovision camera). The most advanced point and the least advanced point obtained from the lateral vision system are used to limit the area under analysis.

Figure 13 shows the results of the 3D surface reconstruction for the fire that appears in the fig. 9 (*b*).

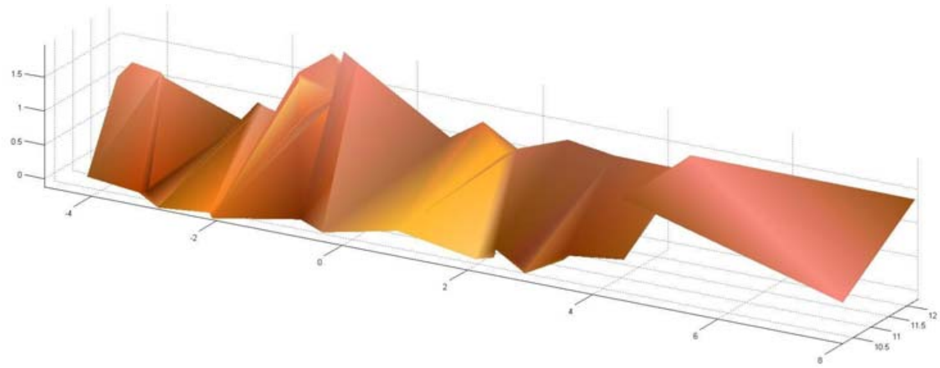


Figure 13. 3D surface reconstruction of a fire front

It gives the position of the fire on the ground, the height and the tilt angle of each point of the fire front. Figure 14 shows the temporal evolution of the fire front profile for the first minutes of propagation of the fire that appears in the fig. 9 (*b*).

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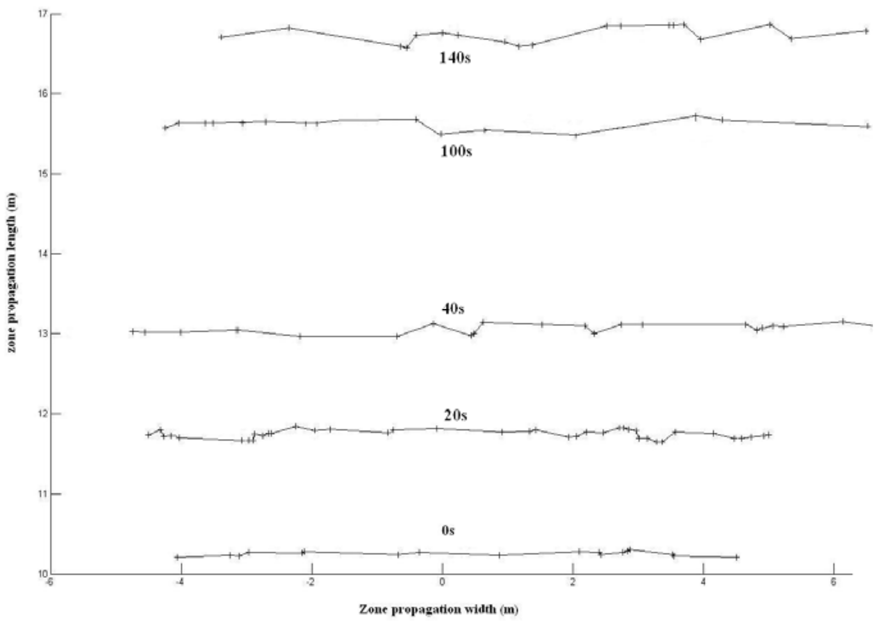

Figure 14. Temporal evolution of the fire front profile

Conclusion

In this paper the work performed in order to develop a metrological system based on stereovision for the estimation of geometrical characteristics of spreading fires is presented. In the case of a laboratory spreading, the vision system is composed of two stereovision cameras positioned respectively in the back position and in the front position relative to the direction of propagation of the fire. With the proposed system, it is now possible to reconstruct the complete form of the fire front in three dimensions and to follow the temporal evolution of the position, the rate of spread, the height, the length, the tilt angle, and the volume of a complex fire spreading at laboratory scale. In the case of field spreading, the vision system is composed of two stereovision cameras positioned respectively in the back position and in the lateral position relative to the direction of fire propagation. Complementary information is obtained from the two cameras. A three dimensional surface reconstruction of the back fire front is obtained and permits to follow the temporal evolution of the fire front position. A Human Machine Interface gives the possibility to an expert to choose from a lateral view the fire points which define the fire area to study. The fire length, the fire height, the fire front width, the rate of spread, the fire inclination angle is estimated from the lateral information.

Ongoing work is being conducted on the fusion of visible and NIR data in order to overcome the problem of losing information when the smoke covers the whole fire front.

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