Automatic Forest Fire Monitoring and Measurement using Unmanned Aerial Vehicles

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Abstract
[Forest fire fighting is a very important issue in which Unmanned Aerial Vehicles (UAVs) can play an important role. The paper presents the use of UAVs as tools for forest fire monitoring. Fire monitoring is defined as the computation in real-time of the evolution of the fire front shape and potentially other parameters related to the fire propagation. The paper shows how an UAV can automatically obtain this information by means of on-board infrared or visual cameras. Particularly, UAVs with hovering capabilities like helicopters are very useful, as they can move to vantage points of view of the fire. Moreover, it is shown how multiple UAVs can collaborate in fire monitoring activities, allowing to cover bigger fires or to obtain complementary views of a fire. The paper presents results obtained in experiments considering actual controlled forest fires in quasi-operational conditions, involving a fleet of three UAVs.]

Keywords: [forest fire monitoring, Unmanned Aerial Vehicles, Cooperative Perception]

1. Introduction

Forest-fire fighting is commonly based on estimations made by fire fighting experts from visual observations. These estimations are subject to a great number of errors due to smoke occluding the flames, human inaccuracy in the visual estimation and errors in the localization of the fire. Recently, new technologies have been applied to fire fighting. However, many of these technologies still have different practical problems for their use in operacional conditions, such as low reliability, high costs and others.

Unmanned Aerial Vehicles (UAVs) can play an important role for forest fire response. They have been already successfully demonstrated for fire detection, localization and observation (Ambrosia et al., 2003; Merino et al., 2005, 2006). In this paper, it is shown how these vehicles can be very helpful in fighting operations once a fire has been declared, participating in fire monitoring tasks. Fire monitoring is related to the computation in real-time of the evolution of the most important parameters related to the fire propagation. Among the most important parameters for fire fighting management are: the shape and position of the fire front, its rate of spread (how this front evolves with time) and the maximum height of the flames (Viegas, 1998). If available, this information, integrated within a Geographical Information System (GIS), can be used by the fire brigades for fire fighting planning, for instance by predicting the potential evolution of the fire, determining the optimal location of fighting means, etc.

In this paper an automatic system that makes extensive use of UAVs and computer vision is proposed for online fire monitoring and measurement. The extension of a forest fire can be very large, so the system can integrate information from several UAVs that can collaborate to cover the fire from complementary points of view. The main objective of this system is, then, the estimation, in real-time, of the evolution of the fire front in geographical coordinates. The paper begins with a description of some current automatic approaches in the literature. Then, it presents the system for multi-UAV fire monitoring, and describes with some further detail the data fusion and image processing techniques employed. Results from experiments involving controlled forest fires are described at the end of the paper, before the conclusions.

1.1 Related work

Traditionally, information extraction for fire fighting support has been done by experts, directly on the terrain or analyzing data provided by towers, satellites or other means. More recently, airborne systems are used in order to have a broad overview of the fire evolution, but still the monitoring activities are carried out by people.

Satellite-based systems have been also proposed for forest fire detection (San Miguel Ayanz et al., 2005; Kelhä et al., 2003) and monitoring (Chuvieco and Martin, 1994; Gonzalo, 1998). The temporal and spatial resolutions of these systems are still very low for the requirements of forest-fire fighting in many cases. There are some fire analysis techniques based on computer vision for fires carried out in laboratories, as (Martínez de Dios et al., 2006; Pastora et al., 2006). However, the application of the same techniques to non-controlled outdoor environments is not considered in those papers. A system for fire monitoring using static cameras has been presented by the authors in (Martínez de Dios et al., 2007).

The use of UAVs in forest-fire fighting scenarios has been analyzed in the FiRE Project in the United States. The ALTUS UAV, an evolution of the Predator UAV, has been demonstrated in fire experiments in the FiRE project (Ambrosia, 2002). The data received at the ground station are geo-referenced imagery about the fire, sent through through satellite uplink/downlink channels.

While the FiRE project considers a single and complex UAV with complex sensors on these tasks, the COMETS European project addressed the use of a team of simpler UAVs that cooperate in fire detection and monitoring tasks (Ollero et al., 2005). Very few papers have been identified considering multiple UAVs in the task of fire perception. One of them is the work of Casbeer et al. (2005), where the feasibility of the application of a team of small (low altitude, short endurance) UAVs to cooperatively monitor and track the propagation of large forest fires is explored. The paper provides simulations using a six degree of freedom dynamic model for the UAVs and a numerical propagation model for the forest fire. However, results in actual fire fighting activities are still to come. Also, Zhou et al. (2005) present a method for orthorectification of images gathered from an UAV, for their application in fire monitoring activities. They discuss specific problems that have to be solved in the case of forest areas, and present very preliminary results on aerial images gathered from a conventional aircraft. However, no actual fire monitoring results are presented.

Figure 1: The UAVs carry mainly IMUs and GPS for navigation. Also, cameras on pan and tilt units for perception.

2. A multi-UAV system for Forest Fire Monitoring

The main objective is to devise a system using multiple UAVs for fire monitoring. This requires to be able to command the different UAVs of the fleet to cover the potential fire in a coordinated manner; and to be able to process the data from the UAVs to obtain an estimation on the evolution of the fire. Therefore, two main systems are involved: a decisional system and a perception system. The decisional system deals with task planning and allocation and coordination within the multi-UAV fleet. The perception system should integrate all the information from the UAV sensors for fire monitoring.

2.1 Vehicles and Sensors

The system developed is able to coordinate heterogeneous UAVs for fire monitoring. The only requirements on the UAVs are the following:

- **Operational autonomy**: the UAVs should be able to fly waypoints and to hover (or pseudohover in the case of planes) at given places autonomously.
- **Localization**: they should be able to localize themselves on the same reference frame.
- **Perception payload**: they should carry infrared and/or visual cameras for perception purposes.

The system has been tested in a multi-UAV fleet of two helicopters and one blimp. In this case, the UAVs are equipped with differential GPS receivers and Inertial Measurement Units (IMUs) which allow them to localize themselves in a common world reference frame.

Besides, for perception purposes the vehicles carry infrared and visual cameras and, some of them, pan and tilt units. Figure 1 shows some examples. As it can be seen, one of the UAVs carry a low-cost non-thermal OEM infrared micro-camera in the far infrared band (7- 14 microns), besides a visual camera.

All the cameras in the system are calibrated before the flights by using artificial patterns. All the images gathered are tagged locally with the composed pose and orientation of the UAV and the pan and tilt unit, timestamps and calibration information.

Moreover, the UAVs carry on board communication devices to be able to receive commands from a ground station, and to send information back to it.

2.2 Decision-making system

The difference between UAVs and manned systems is their ability to perform autonomously certain tasks. As commented above, the system presented here only requires that the UAVs are able to autonomously navigate between waypoints. However, the fire monitoring missions are high-level tasks that require a decisional system for the coordination and control of the fleet of aerial autonomous vehicles of the system. This decisional system implements four main different mechanisms:

- **Task Allocation** arises in multi-UAV systems, where each of the UAVs is able to perform tasks in response to the tasks requests. The issue is to decide which UAV should be endowed with each given task to be performed (for instance, which UAV should go to the different viewpoints to observe the fire). This requires the capability to assess the interest of assigning a certain UAV to a given task. This operation is especially difficult when the decision has to be done taking into account the current individual plans of the UAVs as well as the tasks left to be assigned.
- **Task Planning** is a central issue of the decisional components. It aims at building a sequence of basic tasks to perform, in order to achieve a given high level mission, for instance a fire monitoring mission.

  Within a single agent system, planning is already a complex piece of processing and computations, since the complexity to find an optimal plan is generally very difficult with the usual market-available computation solutions. This is especially true when considering issues like time windows, or uncertainties, in the computation of the plans.
- **Coordination** is a process that arises within a system if given resources (either internal or external) are simultaneously required by several components of this system. In the case of a multi-UAV system, a classic coordination issue to deal with is the sharing of space between the different UAVs, to ensure that each UAV will be able to perform its plan safely and coherently regarding the plans of the other UAVs. For example, as a fire monitoring mission involves complete coverage of a given area, the region should be divided among the available UAVs accordingly with their relative capabilities (such as maximum speed, autonomy, field of view of the cameras, etc.). If other manned aerial means are present, the coordination procedure must take them into account.

  Another important issue is the coordination of tasks between several UAVs: for instance, in the case of monitoring a fire, requiring several synchronized perceptions of the event with convenient locations and orientations of the involved cameras.

  Coordination of space sharing should be performed either continuously or iteratively during the execution of a mission, since contingent events may require to revise and update the plans at any time. Moreover, updating coordination information may eventually also be required to improve the global plan of a group of UAVs, which current individual plans exhibit possible improvements opportunities.
- **Supervision** deals with the management (control) of the tasks execution, in several ways: A first concern is simply to keep the system aware of the tasks processing evolution during their executions; A second concern is to detect the possible tasks failures and (if possible) to react to such events in a way that will prevent the system to fail.

The decisional system employed in our robot team is described in detail in (Gancet et al., 2005; Lacroix et al., 2007), and is able to cope with the previous issues. In Section 4 an example of the capabilities of this system will be shown.

2.3 Perception system description

The system considers all the information gathered by the different UAVs to estimate the evolution of the fire applying data fusion techniques. Fig. 2 gives the big picture. In the system, each UAV will process its images and provide features related to the fire front evolution. All this information is received at the central station, in which the estimation takes place, taking into account all the data from the fleet.

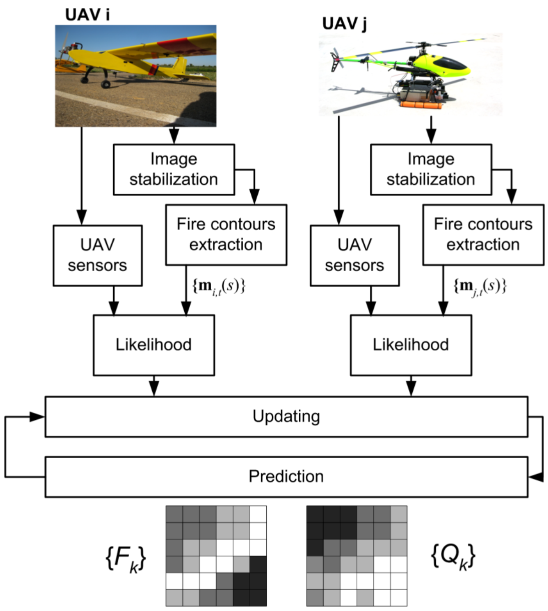

Figure 2: The system estimates two probability grids (fire presence and fuel at each cell). The state of the grids is estimated incorporating data obtained from the fleet of UAVs. The prediction step incorporates the increase in uncertainty due to the motion of the fire.

In order to estimate the evolution of the fire front, the first issue is to devise a convenient representation of the information related to the fire. The fire propagates, changing in size and shape with time. The representation chosen here for autonomous perception consists of an evidence grid. The area of interest is divided into a rectangular grid, in which each cell stores two probability values f_k,q_k. These two values correspond to the probability of having fire at a given cell k, $f_k = p(F_{k,t}= 1)$, and the probability that the cell is burnt $q_k = p(Q_{k,t} = 1)$ (that is, that all the fuel in that cell is completely exhausted). Each cell has an associated 3-D position $\mathbf{r}_k$, given by a Digital Elevation Map (DEM) that is previously loaded in the system (and that can be the result of a previous mapping mission (Hygounenc et al., 2004)).

The system should obtain online the current state of the fire evolution, represented by the particular status of all the cells of the grid. The integration of new information provided by the UAVs is done by using a discrete Bayes Filter for each cell of the grid. The filter has two basic main steps: prediction and updating.

2.3.1 Prediction model

As shown in Fig. 2, the system allows considering a prediction step in the estimation, so that fire propagation models could be included. There are many aspects that influence the propagation of fire, like the slope of the terrain, the moisture content of the vegetation, the meteorological conditions -wind, air humidity, etc- (Viegas, 1998). It is not the objective of this paper to deal with these aspects. The prediction model considered in the experiments shown here is very simple, similar to the EMBYR model (Hargrove et al., 2000) employed in (Casbeer et al., 2005), and considers two different relations: a temporal relation and a spatial relation among cells. Its main objective is, in one hand, to incorporate a memory in the estimation process, so that the fire does not propagate "backwards" through zones previously visited. Also, a spatial prediction is performed in order to smooth the estimated evolution of the fire fronts.

Again, it should be stressed that the main motivation of the motion model is to take into account in the estimation process the uncertainties in the fire front position due to the motion of the fire. It is not the objective to model this propagation. Nevertheless, more complex models of fire propagation could be included within the system.

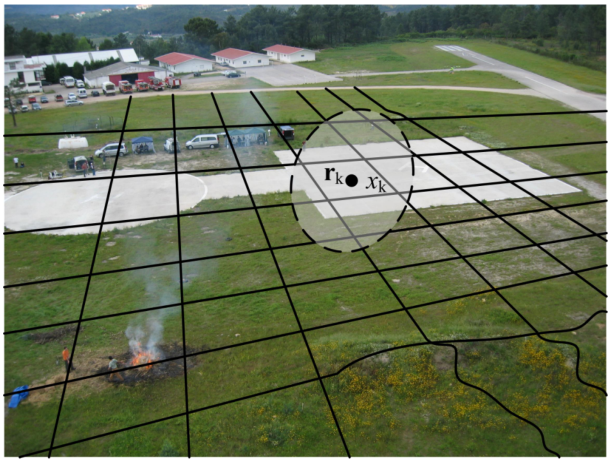

Figure 3: The cells corresponding to a given pixel on the image can be obtained by a geolocation process. With this information, the probabilities of those cells corresponding to pixels segmented as fire will be increased.

2.3.2 Updating step

Whenever new data are received from any UAV of the fleet, the predicted probabilities stored on the cells are updated. The data considered by the system are the fire front contours obtained from the images gathered by the different UAVs. These fire fronts are computed by using the image processing algorithms that will be described in the next section.

The fire fronts obtained on the image plane are geolocated in order to update the corresponding cells of the fire grid map (see Fig. 3). The geolocation is performed by projecting over the DEM of the terrain the pixels of the fire front contour obtained on the images. It is also important to take into account the uncertainties in the geolocated position due to errors on the UAV and camera pose.

The updating step requires the determination of the measurement models or likelihood functions for the different sensors; in this case, for the infrared and visual cameras on board the UAVs. The likelihood of the fire contours in pixel coordinates is considered differently depending on its origin. As infrared images are not affected by smoke (which is transparent at these wavelengths), it is possible to employ negative information from the contours detected (that is, if nothing is obtained on the image plane it is very likely that there is no fire), which is not the case of visual images. The capabilities of the sensors for fire front contour detection are modeled by the values P_D (probability of detection) and P_F (probability of false positive detection). By considering P_F it is possible to use negative information in the estimation process. The final effect of the updating step is that whenever a camera detects fire on a given cell the probability of fire for that cell is increased, while the probability of other cells is decreased if negative information is available.

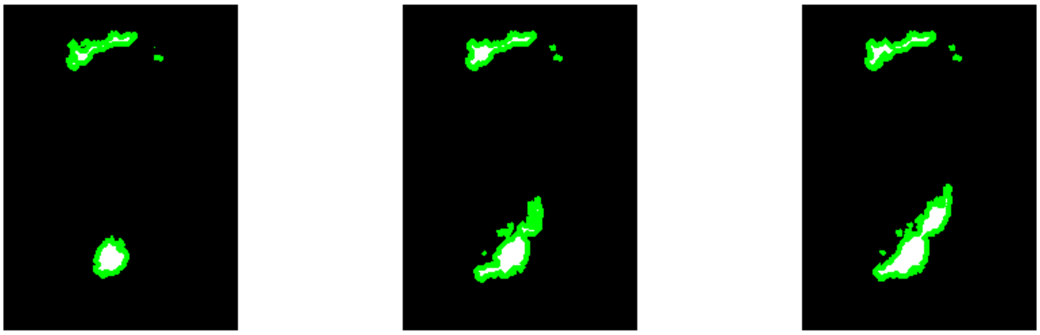

Figure 4: The fire front shape can be obtained from the boundaries of the burnt zone. The figure shows the evolution of the burnt zone during one experiment.

2.3.3 Prior belief state and fire front shape computation

The grid is usually initiated setting the probabilities f_k and q_k to zero for all cells of the grid. Nevertheless, it is straightforward to include prior knowledge into the grid for estimation. For instance, if monitoring is initiated after a fire detection mission (Merino et al., 2006), the f_k value is set to one for the cells corresponding to the initial estimated position of the fire. Also, knowledge about firewalls can be included into the q_k values of the grid, setting the burnt value to one for places that cannot be crossed by the fire.

On the other hand, it is important to obtain the estimated position of the fire front in geolocated coordinates given the current estimated probabilities from the grid (for instance, to communicate it to the fire brigades). The fire front should be on the boundaries of the burnt zone. Also, the position of the fire front should be coherent with cells that maximize the probability of fire at a given moment. Therefore, the procedure determines the boundaries of the burnt zones as the contour of regions of cells with burnt probabilities $q_{k;t}$ over a given threshold (see Fig. 4). These boundaries can be obtained with classical tools for thresholding. From these positions, the final fire front is obtained by considering connected cells on the boundary with high fire probability f_k.

3. Fire information extraction from on-board cameras

3.1 Fire contours extraction

The information about the fire front position is encoded in the images gathered by the UAVs as the contour of fire regions on the image plane. Each UAV process its local images to obtain this information, which is employed to update the probabilities of the grid cells, as indicated above. The main step for obtaining the fire contours is a fire segmentation algorithm that is applied over the images gathered by the cameras.

The infrared camera carried by the UAVs is a low-cost OEM non-thermal camera. It does not provide temperature measures but estimations of the radiation intensity throughout the scene. Black and white colours represent low and high radiation intensities, respectively. Thresholding is then proposed for fire segmentation. For robust fire segmentation, the thresholding technique should consider the particularities of the application. The solution adopted was to use the training-based thresholding method described by Martínez de Dios and Ollero (2004). Its main idea is to extract the particularities of a computer vision application and use them to supervise a multiresolution histogram analysis. The training stage requires a set of training images and their corresponding desired threshold values given by an experienced user. The training stage identifies the conditions under which pixels should be considered to belong to the object of interest. These particularities are introduced in a system via the ANFIS training method (Martínez de Dios and Ollero, 2004).

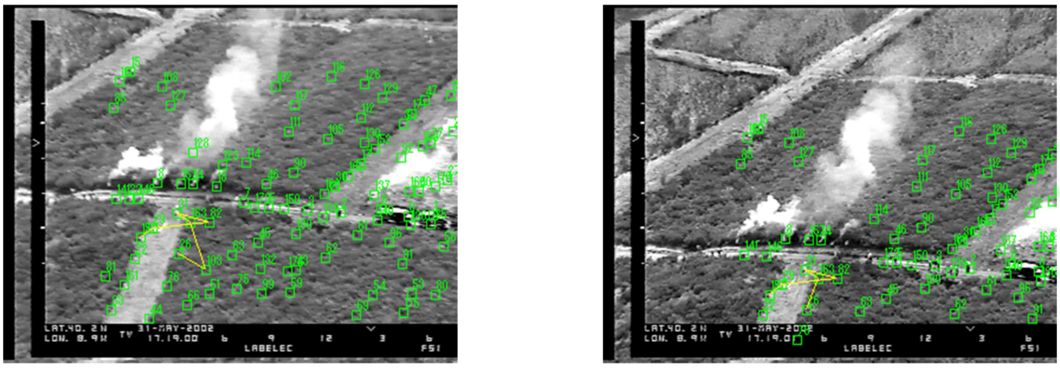

Figure 5: Interest points extracted and tracked in two consecutive images to obtain a sparse image motion field. With this motion field, it is possible to compensate the image motion due to the vibrations.

The technique used for colour images is also a training-based algorithm, similar to (Phillips et al., 2002). In the training stage, a RGB histogram is built by adding Gaussian-type distributions centred at the RGB coordinates of the pixels considered as fire in the training images, while subtracting a similar distribution for the colours of the pixels of the background. Finally, this RGB histogram is thresholded and a look-up table for the RGB color space is built. The look-up table contains a Boolean value indicating whether the color represents FIRE or background, and is used in the application stage to classify the pixels.

Both algorithms are thoroughly described in (Martínez-de Dios et al., 2005). After this step, the contour of the segmented regions is obtained. However, this contour is further characterized in order to distinguish the pixels of the contour related to the fire front and the pixels related to the top of the flames, therefore obtaining the height of the flames in pixel coordinates. The dynamic properties of the fire base and the flames are used for this characterization. The position of the fire-base pixels on the image plane generally change more slowly than the position of the flame pixels (as the flames flicker). The application of a temporal low-pass filter over a sequence of consecutive segmented images is therefore used to filter out the flame pixels.

As a result of the feature extraction algorithms, the measurements provided by each camera on board the UAVs are the pixels corresponding to the fire front.

3.2 Eliminating image vibrations

Considering UAVs with hovering capabilities, unavoidable control errors, turbulence and vibrations produce changes in the camera position, which leads to image motion. This motion can affect to the previously described algorithms and therefore, it is necessary to cancel it. Electro-mechanic systems can be used to cancel vibrations, but these systems are usually heavy, expensive and have a residual vibration.

Image processing procedures can be used for software-based image motion estimation and cancellation. This can be achieved if the apparent motion between consecutive images is computed. In this system, a sparse image motion field is computed by a feature matching algorithm. Figure 5 shows the features employed. Then, this sparse motion field is used to estimate a model of the motion of the complete image. Finally, the model is applied to all pixels to warp the current image to a common frame, therefore eliminating the background motion between the current image and the previous one (Ollero et al., 2004; Ferruz and Ollero, 2000). This way, it is possible to obtain stabilized image sequences in which analyze the evolution of the fire front in pixel coordinates.

Figure 6: Left: the three UAVs that participated in the experiments in a coordinated flight. Right: during the demonstration, small controlled fires were performed.

4. Description of the experiments and experimental results

4.1 Multi-UAV fire monitoring results

The system described in the paper was tested with a team of small-size UAVs. These fire monitoring activities were included in a more general fire fighting mission, designed to demonstrate the feasibility of a team of UAVs in this kind of scenario. In the mission, three UAVs participated: the autonomous helicopter Marvin (Remuß et al., 2002), Heliv (Ollero et al., 2003) and the blimp Karma (Hygounenc et al., 2004) (see Fig. 6, left).

In the general mission, firstly one of the UAVs (Marvin) is sent over a zone for surveillance. Marvin patrols the zone using a simple fire detector, looking for fire spots.

After Marvin detects a potential fire (see Fig. 6, right), Heliv is sent to the same place for confirmation purposes (by using sensors of different modalities, see (Merino et al., 2006)) and to localize precisely the fire. After the fire is confirmed, a fire monitoring mission is generated for Marvin, Heliv and Karma, involving synchronization tasks to take and process pictures of the event from the correct viewpoints at the same time. The decisional layers of the vehicles (Gancet et al., 2005) manage the task planning, allocation and the synchronization signals between UAVs in a decentralized manner, and also the generation of the adequate viewpoints for monitoring the fire, covering the detected alarm from several complementary directions. When the synchronization is correctly achieved, Marvin and Heliv begin to obtain pictures of the fire simultaneously and for a given time. Also, Karma is commanded to take images of all the area from a high vantage point.

The pictures from the UAVs are processed by a using the techniques described in this paper. Each UAV, locally, stabilizes the images captured by its cameras (Section 3.2) and processes the results obtaining an estimation of the position of the fire front in pixel coordinates. The data from all the UAVs are sent to the central station, where all the information is fused for the estimation of the evolution of the fire. Figure 7 shows the images of the same fire from the three UAVs, and how the fire contours are correctly extracted.

After the time for taking pictures has expired, Marvin and Heliv are commanded to return to home and to land. At the same time, a mapping mission is generated for Karma. Afterwards, the mission is terminated.

The full mission, involving fire detection, localization and monitoring is performed with not intervention of the operator, except for the initial plan of the mission. The experiment demonstrates the cooperation of 3 UAVs for fire fighting, involving fire detection and monitoring.

Figure 7: Top: left, image from Marvin, after stabilization and feature extraction; middle, image from Heliv after stabilization and feature extraction; right: image from Karma. Bottom: details of the extracted contours. Green: fire front. Red: top of the flames.

4.2 Gestosa results

In the previous experiments, the controlled fires performed are of small scale, and it is difficult to appreciate an evolution on the fire front, although Fig. 7 shows how the shape of the fire is correctly estimated. The techniques described have been also validated in many controlled medium-scale forest fire experiments carried out in Serra da Gestosa (Portugal). In these field experiments, square plots of up to 150 by 100 meters were burned under controlled safety conditions. The experiments mobilized significant resources including 80 firemen and 5 firefighters trucks. A more detailed description of these experiments can be found in (Viegas et al., 2002).

Figures 8 and 9 shows results of one of these experiments. In it, a plot of approximately 10000 square meters was burnt. In this case, a helicopter is commanded to gather aerial images. Also, a frontal view from a static camera is available (emulating a second UAV). A linear fire front is ignited on the lower part of the plot, and the fire propagates uphill.

Figure 8 shows several frames gathered from the helicopter, after the application of the image stabilization and feature extraction algorithms. It can be seen how the stabilization algorithm effectively removes the motion induced by the helicopter. It can be also seen how the fire front shape is adequately extracted from the images.

The fire probability grid evolves as these features are gradually considered. Figure 9 shows the estimation of the fire front shape each 20 seconds, compared to a manual estimation based also on the images (in order to validate the automatic algorithms). Figure 10 shows the evolution of the most advanced point of the fire front with respect to the lower firewall in georeferenced coordinates. These experiments show the applicability of the techniques to fires of an scale close to operational conditions.

Figure 8: Frames 3, 44, 77, 144 and 219 of the aerial sequence gathered during the fire experiment 520, after automatic stabilization. The extracted fire front contour is also shown.

5. Conclusions

This paper has presented a perception system for the problem of forest fire monitoring using a team of UAVs. The system integrates the information from the fleet to obtain an estimation in real time of the evolution of the forest fire. The system has been tested in actual experiments involving controlled fires. In these experiments, a fleet of three UAVs is considered.

One of the main conclusions of the paper is that it is feasible to develop UAVs for forest fire perception. The experiments show that UAVs can be very helpful for fire fighting activities like fire monitoring, as they can cover the gap between the spatial scales given by systems based on satellites and those based on cameras on towers. The UAVs can adapt their deployment to avoid the inconveniences of other approaches, like the presence of smoke, or to cover the more convenient places.

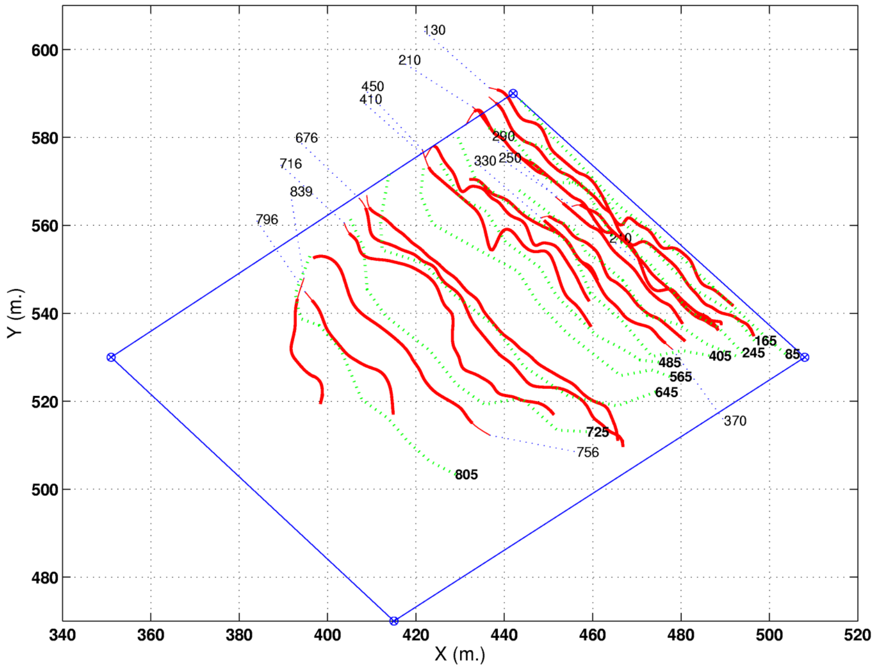

Figure 9: Evolution of the fire front (in georeferenced coordinates) for plot 520 estimated from the images gathered by the helicopter (solid) and compared with the front obtained with static cameras on ground (dashed).

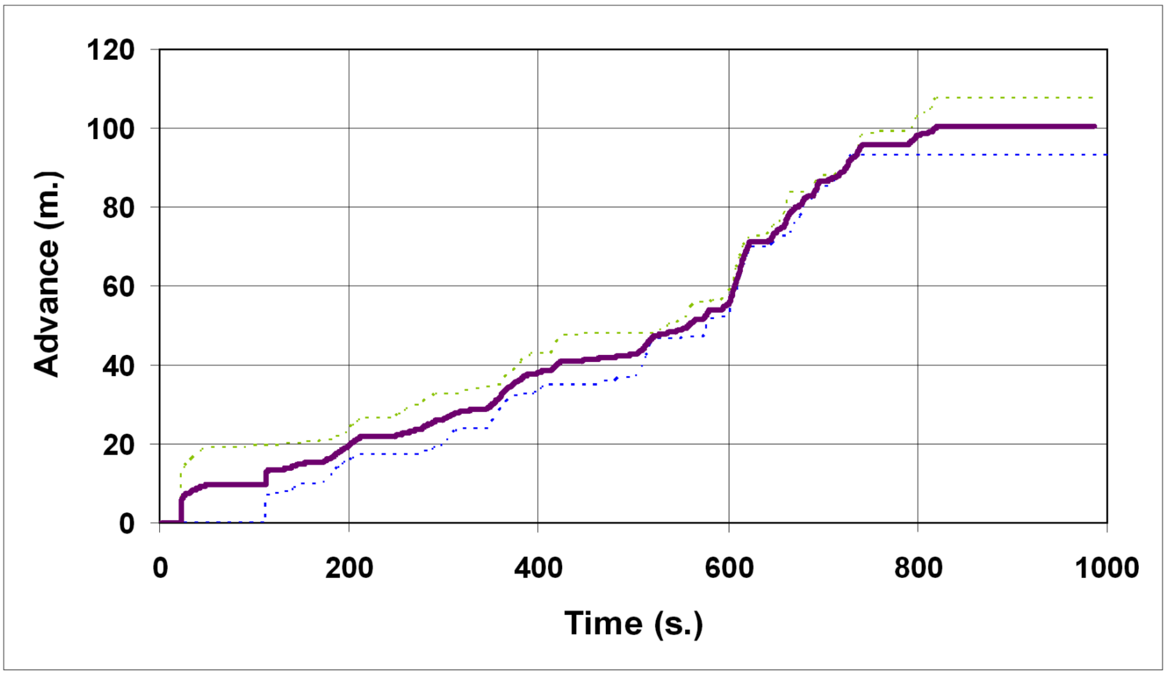

Figure 10: Evolution of the most advanced point of the fire front with respect to the coger firewall for experiment 520. Estimations from the aerial and frontal static cameras (dashed) and combined estimation (solid).

Some issues should be discussed. One of them is the scalability of the proposed approaches. The experiments shown in the previous sections can be considered close to the operational conditions, although on a lower scale. In order to apply the techniques in real situations, UAVs with higher endurance are required. Nowadays there are UAVs, mainly developed for defense and security applications, that have the required endurance, and therefore the extension of the techniques for their use by environment management agencies seems affordable. For instance, in the FiRE project (Ambrosia, 2002) a Predator UAV is used as a platform for forest fire surveillance. Some work is also required to develop robust controller to be applied to flights close to the fire, usually under strong wind gusts.

Another potential question is if the use of several UAVs offers advantages against the use of one complex UAV. For the case of fire monitoring, employing several UAVs allows obtaining different and complementary views. Moreover, small UAVs could be employed by fire brigades to, at least, obtain local views of areas difficult to be accessed. Also, several cheap UAVs can carry a bench of sensors that, on the other hand, would require an usually more expensive UAV with higher payload.

In discussions with different reviewers of the related projects, the question came up of whether autonomy is required at all for this kind of tasks. The answer is that it depends of the tasks to be performed and the flight conditions. Teleoperated vehicles can be very helpful for certain tasks, for instance for helping fire brigades to obtain close views. In any case, autonomous perception functions are required if no communication links or not enough bandwidth is available. Also, out-of-sight flights require autonomous navigation capabilities, as well as night navigation. If the UAVs have to cover wide areas, then at least operational autonomy is required. The importance of higher degrees of autonomy is more evident when considering fleets with a high number of UAVs. Controlling the fleet would require quite complex control centres or quite an amount of people if the UAVs are not endowed with decisional capabilities.

Although the tested system is centralized, the techniques described in this paper can be used to decentralize the grid estimations, which would make the system scalable to a higher number of UAVs.

Acknowledgments

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