

Forest Fire Monitoring System Based on UAV team, Remote Sensing, and Image Processing

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Abstract—This work presents the fire monitoring and detecting system for tactical forest fire-fighting operations based on a team of unmanned aerial vehicles, remote sensing, and image processing. The idea of such a system and its general parameters and possibilities are described. Functions and missions of the system, as well as its architecture, are considered. The image processing and remote sensing algorithms are presented, a way for data integration into a real-time DSS is proposed. The results of experimental research of the prototype system are presented. The combination of multi-UAV-based automatic monitoring, remote sensing and image processing techniques provides required credibility and efficiency of the fire detection.

Keywords—unmanned air vehicles; forest fire monitoring; remote sensing; image processing; fire detection.

I. INTRODUCTION

The first decade of XXI century is characterized by activation of forest fires whose effects are damaging to the environment and which require intervention methods and techniques adapted to the conditions and needs of each incident. A number and intensity of forest fires are significantly increasing year by year due to a growth of human activity and climate changes. Forest fires response operations are becoming increasingly important but challenging because they are traditionally based on visual observations and decision-makers estimations that are made under the high responsibility conditions in a lack of time. Thus, the problem of forest fire detection, monitoring and forecasting is very relevant for many countries. It stipulates the development of real-time decision-support systems (DSS) for the forest fire monitoring, detection and response.

However, developing such kind of DSS is a complex and non-trivial task because the forest fire is a process with unpredictable behavior. Taking into account inaccurate or missing data describing fire, incomplete scientific understanding of fire behavior, a forest fire is poorly modeled and predicted. This excludes the use of well-studied classical decision support approaches based on models, rules, etc. In such conditions, the efficiency of forest fire operations strongly depends on the availability of online fire monitoring and detecting tools. To build such tools, we can use a suite of modern methods and techniques, such as remote sensing, image processing, unmanned air vehicles (UAVs), etc., which should work synergistically. Thus, the research of ways of developing an UAV-based online forest fire monitoring and detecting system is the topic of our current interest.

II. LITERATURE REVIEW

The most important problem of each forest fire response operation is a timely fire detection. The success of a fire suppressing depends essentially on its early detection, which makes it possible to start suppression as quickly as possible while the fire is still small and well-controlled [1]. For this purpose, forest fire monitoring can usually be carried out as the observation of a wildland area in terms of fire activity. The monitoring process generally includes such activities as searching for new forest fire starts (i.e., from satellite imagery, watchtowers or aerial patrols) and detecting of fires, which is the task of determining that a fire exists and triggering an alarm to start a fire response operation. Thus, fire detection task can be reduced to resolving uncertainty about whether a fire exists or not [2]. Obviously, to start a response operation on the fire it also needs to be localized and characterized, so the fire monitoring task can also be aimed at the real-time computation of an evolution of the most important parameters related to the fire propagation based on the online observations [3].

Traditionally, satellite and airborne systems are used in order to have a broad overview of the forest fire evolution, but the monitoring activities are still carried out mainly by people. Watchtowers need to be carefully placed to ensure adequate visibility and are expensive and inflexible; thus they are usually allocated for monitoring high-value or high-risk situations [4]. A ground-based system for fire monitoring using static cameras has been presented in [5]. Given the fact that large-scale forest fire management requires a great number of cameras, the price and complexity of such system are unacceptable. Satellite-based systems [6] have been proposed for forest fire detection and monitoring, but the temporal and spatial resolutions of such systems are very low for the requirements of forest-fire fighting. Manned aircraft are large and expensive; their use highly depends on the weather conditions and requires the presence of aerodromes [7].

One of the new approaches to forest fire monitoring is online UAV-based monitoring using remote sensing techniques [8]. Using remote sensing data gives some advantages: the data acquiring is often less expensive and faster than from the ground; remote sensing allows capturing data across a wider spectrum that can be seen by the human eye; it can cover large areas including far away and inaccessible areas; remote sensing provides frequent updates. Recent years have seen a great progress in the field of using UAVs for forest fire monitoring, detection, and even fighting [9]. UAVs can perform long-time,

monotonous and repeated missions beyond human capabilities. However, uncertainty and distortions of received image frames due to vibrations and turbulence, as well as the inability to measure directly the parameters required for decision-making are significant drawbacks of this approach [10].

Thus, the integration of UAVs with remote sensing techniques can provide rapid, mobile, and low-cost powerful solutions for the forest fire monitoring and detection tasks [11]. Therefore, many researchers pay increased attention to using UAVs. The use of a single and complex UAV with sophisticated complex sensors has been investigated in FIRE project, while the cooperative use of a simpler UAVs' team was explored in European COMETS project and in a number of other projects surveyed in [7]. Many works related to the detection, modeling and forecasting of forest fires were carried out at the National University of Civil Protection (Kharkiv, Ukraine). As well, over the past few years, a project has been implementing at the Ukrainian Research Institute of Civil Protection (Kyiv, Ukraine) concerning the monitoring of fires and providing operational communication during the emergencies' response based on UAVs. Despite the positive results, which have shown the possibility of using UAVs in the forest fire response operations [12], many issues related to UAV-based forest fire monitoring and detection systems, including their remote sensing and image processing techniques, still remain insufficiently investigated, so need further research.

III. PROBLEM STATEMENT

Forest fire-fighting operation should start as early as possible and should be done as fast as possible to minimize the damage caused by fire. By means of the modern sensory technologies, a forest fire can be quickly and accurately detected. For this, UAVs can provide a full range of multi-sourced data for fire monitoring [13], which have the form of streams of great volumes and can be characterized by the following features [14]:

- 1) *volume*: the data are characterized by their great volume;
- 2) *variety*: the remote sensing data are multisource, multitemporal, and multiresolution;
- 3) *velocity*: the data are generated and processed at a high rate and should be analyzed in a real time;
- 4) *continuity*: the data come from sensors on a continuous basis.

We assume that the combination of automatic monitoring system based on UAVs and remote sensing techniques with an approximate model of forest fire spreading [15] can provide the required credibility and efficiency of the fire detection synergistically. The aim of this work is to investigate remote sensing and image processing techniques for a multi-UAV-based monitoring system for tactical forest fire-fighting operations considering the joint use of UAVs, remote sensing of different types and GIS-based common terrain model, and their integration with the approximate fire-spreading model.

IV. FIRE DETECTION PATROL MISSION

The multi-UAV-based tactical forest fire monitoring system should perform the fire detection in order to find

potential ignitions, detection of fire, triggering an event, and initializing further monitoring of the fire. In general, the forest fire monitoring system must provide real-time information to decision makers for the forest fire response operation.

The fire detection task can be generally broken down into two successive stages: fire search and fire confirmation. We assume that each UAV will perform a certain mission at each stage. Thus, in this paper we consider two types of missions:

- patrol mission (surveillance over the large region and performing the fire detection);
- confirmation mission (resolving uncertainty about whether a fire exists or not).

In the patrol mission, each involved UAV has its own flight plan that contains a pre-planned path as a sequence of waypoints. Flying along the pre-planned path, UAV observes terrain using onboard sensors and tries to identify fire automatically. It is clear that the flight plan generally is strictly bounded due to some limitations of UAVs' capability, such as duration, range, altitude, sensor resolution, etc. Depending on the size and characteristics of the surveillance region, various number of UAV can be involved in patrol mission simultaneously along their own pre-planned paths.

After the fire is detected, confirmation mission begins. In one of the options, the patrol UAV detected the fire can continue its patrol mission further, but it must trigger the event. Other UAVs with hovering capabilities should be sent to the detected fire location to hover at a safe distance and make confirmation. Another option is to change pre-planned paths of the patrolling UAVs to fly by a circle around the detected fire location in order to confirm it. If the detected fire is not confirmed, the patrolling UAVs resume their missions to surveillance of the region. Given the fact that performed missions differ in goals and requirements, we need the UAVs of different types equipped with the sensors of different types with a single ground command center. The basic structure of the multi-UAV-based forest fire monitoring system is illustrated in Fig. 1.

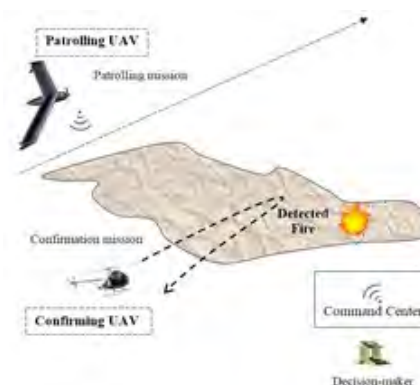


Fig. 1. Structure of the forest fire monitoring system.

The system includes the following components:

- 1) *a multitude of UAVs* (for the patrolling and confirming missions) equipped with the onboard sensors;

2) an infrastructure for the UAV ground support (launch and landing, maintenance) and equipment for the UAVs control;

3) specific algorithms/techniques for remote sensing and image/signal processing;

4) a dedicated ground command center that includes communication/computation equipment, geographic information system (GIS), and decision support system;

5) specific algorithms solving the fire detection, tracking, diagnosis, and prediction tasks.

V. VEHICLES AND SENSORS

Consider the used types of UAVs and sensors. The common requirements on the used UAVs are the following:

- *all-weather suitability*: all UAVs should perform their functions in both night-time and day-time even in the most difficult weather conditions;
- *self-localization*: a common reference terrain model should be used by all involved UAVs for automatic geo-localization of their spatial positions;
- *navigational autonomy*: sophisticated sensors (e.g. GPS receivers, inertial measurement units (IMU)) should be used by all involved UAVs for automatic flying along paths given by ground command center;
- *cooperation*: the UAVs should be able to coordinate their behavior and to cooperate with each other in order to solve their tasks optimally ;
- *payload*: the UAVs should carry all required sensors for fire perception purposes.
- *availability*: all UAVs should be equipped with onboard communication devices that guarantee receiving commands from a ground command center, sending information back to it, as well as exchanging information with the other UAVs.

The general structure of the used UAVs is illustrated in Fig.2. In accordance with the different missions' tasks to be performed, different types of UAV are used for those missions.

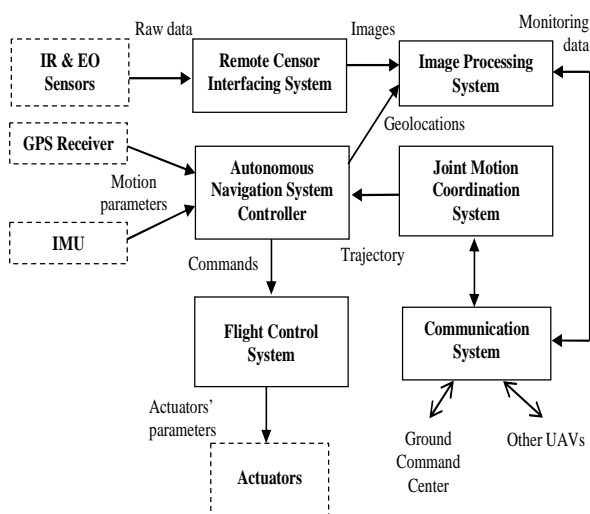


Fig. 2. Vehicle onboard control system

For the patrol mission in order to minimize the solution cost we use fixed-wing micro-UAVs with electric propulsion system having flight ceiling up to 2000 m, cruise speed about 90 km/h, takeoff weight up to 5 kg. This type of UAV provides the flight duration about 2.5 – 3 hours, and flight range with an online connection up to 75 km. It is equipped with a low-cost non-thermal (5-13 μm band) infrared micro-camera and a simple 12-megapixel optical camera with electronically adjustable focus.

We can use the same type of UAV for the confirmation mission. However, the confirmation mission can be performed much easier, faster and more efficient if we send the UAV with hovering capabilities to the detected potential fire location. Equipped with more precision (and, thus, more expensive) infrared and optical sensors, such UAV can hover for some time at a safe distance from the potential fire site and monitor it for verification purposes. Therefore, we use rotary-wing micro-UAVs with electric propulsion system having flight ceiling up to 180 m, cruise speed about 50 km/h, takeoff weight up to 7 kg. This type of UAV provides the flight duration about 1 hour, and flight range with the online connection up to 55 km. It is equipped with a precision gimbal that carries a wideband infrared camera and a 16-megapixel optical camera. A relatively small, but safe enough hovering altitude provides the good applicability of this type of UAV. Due to the higher resolution of the sensors and the closest approach to the observed point, we can achieve a much greater observation accuracy. In addition, this type of UAV can change the point of view relatively quickly, providing a higher efficiency of fire detection and confirmation.

VI. REMOTE SENSING AND IMAGE PROCESSING

The main goal of the forest fire monitoring is to continuously obtain information about the fire activity over a large wildfire region. The fire detection task performing is based on the common terrain model, which is a part of GIS-based DSS.

A. Common Terrain Model

The forest fires arise and spread through the certain area, represented by GIS as a certain terrain. The terrain model is based on the pre-built Digital Elevation Model (DEM) [12].

Firstly, the terrain is divided into a finite set of disjoint spatial objects presented as geometric shapes, which outline boundaries of the certain areas. Such spatial object is named as geotaxon and represents a geo-referenced limited natural part of the terrain with the same physical (or other) characteristics. For example, areas with the same features of the soil can be described as geotaxons of a certain kind. GIS can contain an unlimited number of geotaxons' layers. Secondly, a grid of isometric square cells $D = \{d_{ij}\}$ approximates the terrain and constitutes a certain GIS layer. Thus, each spatial object's location is discrete and bounded to a specific cell. The size $\delta \times \delta$ of each cell d_{ij} can vary, so the terrain scale can also change.

B. Image Processing During the Patrol Mission

During the patrol mission, the main sensor is the non-thermal infrared camera because obtained infrared images are not affected by smoke (the smoke is transparent for the used far infrared wavelengths). Besides that, the infrared camera is workable under either weak or no light conditions.

It does not provide temperature measures but only estimations of the radiation intensity, represented by colors. If a certain cell does not have any radiation, its pixels in the image are black. The appearance and increase of radiation change the pixels' color from black to white. Thus, if there are no white pixel in the image, it is very likely that there is no fire in the corresponding cell. However, some pixels can have grey colors.

At first, the brightness data is averaged within each cell d_{ij} , so the whole cell takes a certain average brightness B_{ij} . Then we use a partial order of grey colors (Fig. 3), which implies the ordinal color scale from black to white mapped on a numerical scale from 0 (black) to 1 (white). Thus, based on the brightness B_{ij} of each cell d_{ij} , we obtain a value μ_{ij} expressing the degree of ignition/burning possibility at this cell.

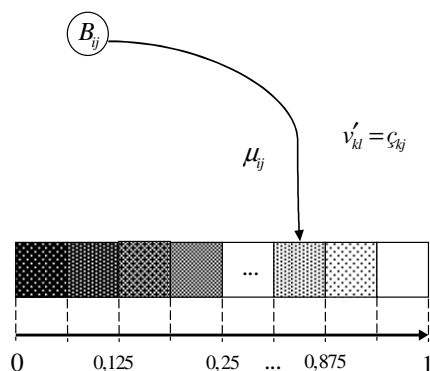


Fig. 3. Partial order of grey colors

Since various superheated or supercooled rocky areas, soils, and water surfaces can distort data obtained from the non-thermal infrared camera, we should simultaneously get data from the optical camera. An obvious feature of the presence of a forest fire is the smoke, observed as a light gray figure like a cone elongated in the wind direction. Thus, the processing of color images obtained by the optical camera is aimed at searching smoke or flame within them.

For this, firstly we define the discriminating interval in RGB space $LG = [RGB(60\%, 60\%, 60\%) - RGB(95\%, 95\%, 95\%)]$, which exclude some distortions caused by lighting conditions. We use texture-based classification method with the color-diffusion evaluation that differentiates smoke and non-smoke based on the counting of the number of pixels, which color belong to the interval LG , relative to the total number of pixels in the cell. These values could be averaged over a certain time interval (for example, 5 sec) for each cell d_{ij} and returned as a degree of ignition/burning possibility η_{ij} ranged from 0 to 1.

During the onboard automatic processing (Fig. 4), on the first step, we perform stabilization of the images. On the next step, we process the infrared and visual images by the above-mentioned methods. On the third step, we perform geo-localization, then geo-rectification. The UAVs' locations can be obtained using the GPS. The positions and orientation of the infrared and optical cameras can be computed based on their orientation angles and IMUs' data. To determine the position of each image pixel we use the

photogrammetric projective transformation that projects all points on the ground described by the DEM. DEM is also used to define the geospatial context (e.g., latitude/longitude/elevation) and timestamps for the geo-rectification. Thus, each image pixel becomes geo-referenced and can be mapped onto the grid. If both cameras are calibrated and DEM is available, we obtain the geo-referenced images in the common terrain model approximated to the cell level.

On the final step, we perform image fusion based on geo-referenced points. The values of the ignition/burning possibility μ_{ij} and η_{ij} that refer to the same cell d_{ij} for both images are combined by absorbing smaller values by larger: $v_{ij} = \max(\mu_{ij}, \eta_{ij})$. Then the array of resulting values v_{ij} should be transmitted to the command center. On the receiving side, we use a training-based threshold selection method to reduce false alarms. Using the given threshold v^* , we consider the fire detected only for the cells, which have greater or equal values of the ignition/burning possibility degree v_{ij} . The training stage could be performed by an experienced decision-maker on a set of training images identifies the conditions, under which the uncertain assessments v_{ij} can be considered as positive.

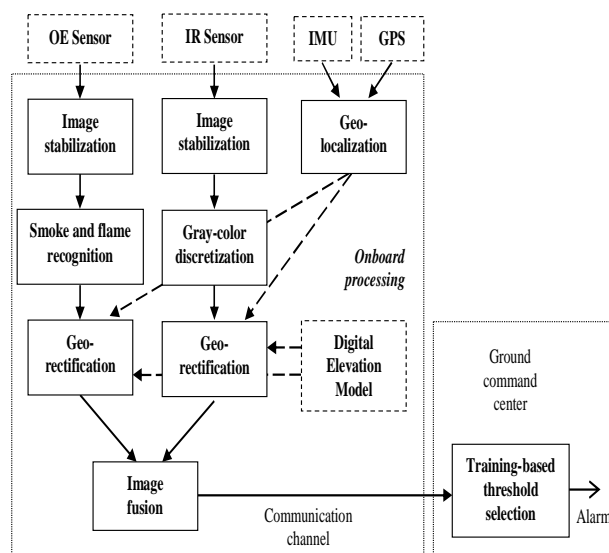


Fig. 4. Image processing during the patrol mission

VII. EXPERIMENT RESULTS

UAV onboard control system prototype was implemented using embedded microcontroller STM32F429 (180 MHz Cortex M4, 2Mb Flash/256Kb RAM internal, QSPI Flash N25Q512). Control center prototype used two servers HP ProLiant ML350 (Intel Xeon E5-2620, 8 cores up to 3 GHz).

The system has been tested with the multi-UAV team (3 drones for the patrol missions, 1 helicopter for the confirmation mission). All UAVs' cameras were precisely calibrated.

The performance of the developed system was studied in the laboratory conditions. It depends mainly on the cell size. The simulation experiment has been conducted varying the cell size from 5 m to 25 m as well as varying a number of discretization level in image processing algorithms.

Obtained results reflect that the bottleneck is the significant computational load of the UAV onboard control system. Further increase in processing power is limited by the available characteristics, and it requires to move some image processing to the ground command center.

However, the developed system has demonstrated the satisfactory probability of correct forest fire detection ($\approx 92\%$) in near-real-time conditions (processing time less than 2 min) with 10 m cell size and 16 levels of the color discretization.

Using the developed system, we achieved a good accuracy (up to 96%) of the fire spreading prediction for various terrains and weather conditions. Thus, the result of the experiment has shown that the developed system can provide required credibility and efficiency of fire prediction and response.

VIII. CONCLUSION

It can be concluded that the remote sensing techniques, which offer a variety of ways to detect and monitor forest fires, provide a great promise in solving the problems of forest fire management in real-time decision support systems.

It is shown how UAVs can be very helpful in fire-fighting response operations participating in fire monitoring and detection tasks. The combination of the multi-UAV-based automatic monitoring system and remote sensing techniques with an approximate model of forest fire spreading can provide the required credibility and efficiency of a fire detection and response. The developed system has demonstrated the satisfactory probability of the forest fire detection ($\approx 92\%$) in near-real-time conditions with processing time less than 2 min, 10 m cell size and 16 levels of the color discretization.

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