Forest Fire-Fighting Monitoring System Based on UAV team and Remote Sensing

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***Abstract*—This work presents a monitoring system for tactical forest fire-fighting operations based on a team of unmanned aerial vehicles and remote sensing techniques. Functions and missions of the system, as well as its architecture, are considered. Image processing and remote sensing algorithms are presented, a way for data integration into a fire-spreading model in a real-time forest fire response decision support system is proposed. The combination of automatic monitoring and remote sensing techniques with an approximate fire-spreading model can provide required credibility and efficiency of fire prediction and response.**

***Keywords*—unmanned air vehicles; forest fire monitoring; remote sensing; image processing; fire-spreading model.**

I. Introduction

A number and intensity of forest fires are significantly increasing year by year, they become bigger, more dangerous, and more costly to put out. Forest fires response operations are challenging because they are traditionally based on visual observations and decision-maker's estimations. Due to exposure to smoke, flame, and high temperature, visual observations are usually ambiguous, imprecise, incomplete, and inconsistent, while instrumental measurements are expensive, difficult, and dangerous. Besides that, decision-makers often operate under the high responsibility conditions in a lack of time. It stipulates the development of real-time decision-support systems (DSS) for the forest fire response.

Since the forest fire is poorly modeled and unpredictable process, classical decision support approaches bring a little assistance, so the efficiency of forest fire operations strongly depends on the availability of online monitoring and measurement tools. To build such tools, a suite of the modern methods and techniques, such as remote sensing, geographical information systems (GIS), and unmanned vehicles can be synergistically used. Thus, the research of ways of developing the online forest fire monitoring and diagnostic system for real-time response operations is the task of our current interest.

II. Literature Review

The central issue of the forest fire response operation is a fighting planning. To solve the problem, decision-maker needs to know, in what direction and at what speed the fire front will spread at the next time. To do this, he needs to estimate how some important parameters (e.g. actual shape of the fire front, its rate of spread, the height of the flame, etc.) evolve with time. A number of approaches to solve such task are currently known.

A predictive fire modeling is the most common approach based on the use of physical fire-spreading models, the most famous of which is Rothermel model [2]. Such models allow obtaining exact values of some fire properties (e.g. spread rate) only if the exact values of initial data are known. Unfortunately, those data are not usually available for direct measurements. Vector models [3] strongly assume that fire spreads according to a well-defined growth law. They also significantly depend on the accuracy of the initial data. Fractal and wave extensions of vector models [4] less depend on the accuracy of observations, but they are more computationally intensive, so they cannot be used in real-time. Cellular automata models [5] demand the constant conditions of weather, fuels, and topography, which really vary spatially and temporally. Thus, the predictive fire modeling approach is not suitable for decision-maker who solves the planning task for forest firefighting in real time.

Another known approach is online forest fire monitoring using remote sensing techniques [6]. The forest fire monitoring is the activity aimed at the real-time computation of the evolution of the most important parameters related to the fire propagation based on the online observations. All known approaches to the forest fire monitoring have their drawbacks. For example, ground-based systems, which use static cameras [7], have unacceptable price and complexity. Satellite-based systems [8] have low temporal and spatial resolutions. Manned aircraft [6] is large and expensive, they depend on the weather conditions and require the presence of aerodromes.

Recent years have seen a great progress in the field of using unmanned aerial vehicles (UAVs) for forest fire monitoring, detection, and even fighting [9]. UAVs can perform long-time, monotonous and repeated missions beyond human capabilities. However, distortions of received images due to vibrations and turbulence and inability to measure directly parameters required for decision-making are drawbacks of this approach [10]. Thus, the integration of UAVs with remote sensing techniques can provide rapid, mobile, and low-cost powerful solutions for various forest fire tasks [11]. The use of a single and complex UAV with

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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 [6]. Despite their positive results [12], many issues related to UAV-based forest fire monitoring systems, including their architecture, suitable platforms, sensors, remote sensing and image processing algorithms, still remain insufficiently investigated today, so this needs further research.

III. Problem Statement

Early detection and rapid extinguishment of the forest fire can minimize damages caused by fire. After the forest fire is detected, decision-maker has to estimate its parameters such as fire front location, fire site size and perimeter, flame length and height, hotspots and their location, and others. Such estimates projected onto a terrain map are essential for fire-fighting planning [13]. The rate of spread is the significant parameter because it characterizes a fire behavior, so most of the developed systems are focused on the evaluation of this parameter. An aforementioned literature review has shown that decision-maker cannot obtain exact estimates in real time using both automatic monitoring system due to essential uncertainty or predictive fire modeling due to computational complexity and a lack of initial data. However, in real conditions, decision-maker does not require precise estimates of fire parameters, but he needs a prediction how the fire will spread. Therefore, we do not need the accuracy of prediction, but its credibility, and we can estimate indirectly some parameters, which cannot be directly measured. Thus, using modern methods of remote sensing, in contrast to analogous fire monitoring systems, we will not only obtain approximate position of the fire front dynamically but also the plausible estimates of fire parameters for the approximate forest fire spreading model [1]. We assume it can provide the required credibility of the prediction synergistically.

The aim of this work is to develop an architecture of 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. We define and describe functions and missions of the system and its architecture, UAVs and sensors, an organization of the remote sensing and image processing techniques in the frame of the real-time DSS for the forest fire response.

IV. The System Architecture

The multi-UAV-based tactical forest fire monitoring system should perform the following functions:

- fire detection (finding potential ignitions, detection of fire, triggering an event, and initializing further monitoring of the fire);
- fire monitoring (determining the fire's location and extent, observing and tracking its evolution);
- fire diagnosis (obtaining detailed information about the fire, estimating its important parameters);
- fire prognosis (predicting the future fire evolution in real-time).

The objectives are to use the heterogeneous team of UAV to detect and track forest fires, measure their features and predict their future evolution. In general, the forest fire monitoring system must provide real-time information to decision makers for response operation planning. In the future, the team of UAV can be immediately involved in firefighting.

System operation can be generally broken down into three successive stages [10]: fire search, fire confirmation, and fire observation. Accordingly, it is assumed that each UAV will perform a certain mission at each stage. Three main types of missions are envisaged:

- patrol mission (surveillance over the region and fire detection);
- confirmation mission;
- monitoring mission.

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, a 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.

If the fire is confirmed, the fire monitoring mission starts. This mission usually requires multiple synchronous information obtained by UAVs from different points of view, therefore a couple of UAV should be involved to execute the mission. It allows obtaining information about the fire continuously. Required estimations of the fire features should be delivered to decision-makers through the ground station and DSS to better guide firefighting efforts. 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.

The system includes the following components:

1) a multitude of UAVs (for the patrolling, confirming, monitoring 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.

Consider the used types of UAVs and sensors.

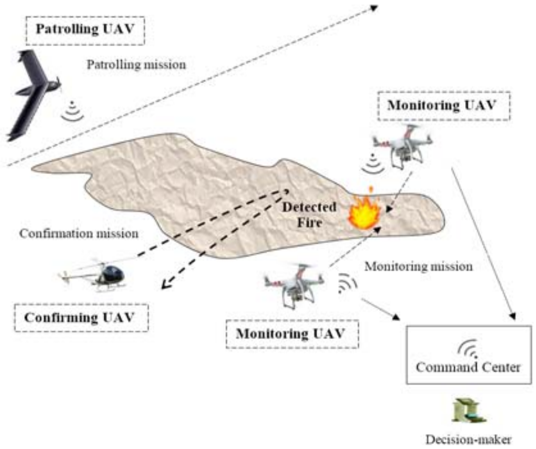

Fig. 1. Structure of the forest fire monitoring system

V. VEHICLES 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.

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.

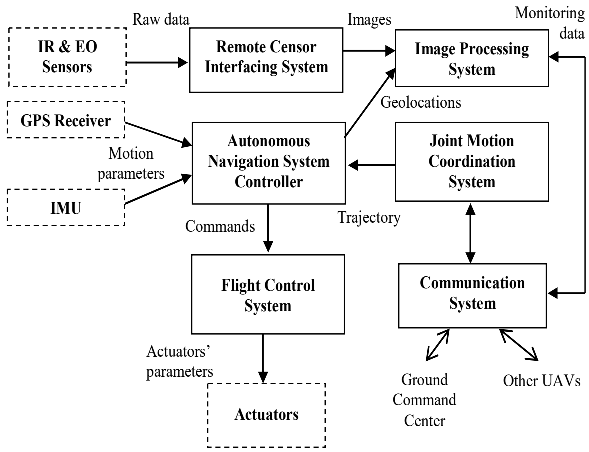

Fig. 2. Vehicle onboard control system

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 precise (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.

For the monitoring mission, it is essential to obtain clear images without distortions arising from turbulence and vibrations. Besides that, we need to estimate some parameters, which were not necessary for the previous missions. Obviously, monitoring UAVs should have hovering capabilities. Thus, we use multi-rotary-wing UAVs (octocopters) having flight ceiling up to 120 m, speed about 20 km/h, and takeoff weight up to 15 kg. It provides the flight duration about 2 hours, and flight range with the online connection up to 25 km. It is equipped with a remotely-controlled precision damped gimbal that carries both a wideband non-thermal and a thermal (four-band, 5-13 μm) infrared cameras, as well as high-resolution optical camera with pan and tilt units. The thermal infrared camera has temperature measurement range up to 1250°C with the accuracy about 1°C at the top of the range.

This type of UAV also can use lidar sensor that provides advanced sensing capabilities, and wide-range weather sensors ensuring a very accurate measurement of temperature, humidity, wind speed, and direction, etc. It provides a sufficiently long hovering time but has a limited speed and flight range. Fortunately, fire-fighting brigades use UAVs of this type locally, immediately on the terrain, so the wide flight range is not necessary. The cost of the UAV of this type is much higher than UAV of the other types. However, they are used relatively little during a fire monitoring only, and cheaper solutions can be used to solve the patrol and confirmation tasks.

VI. Remote Sensing and Image Processing

The main goal of the forest fire monitoring is to continuously obtain information necessary for the approximate fire-spreading model proposed in [1, 15] in order to predict the future evolution of the fire. The model represents spatiotemporal relations among cells. It is known that fire spreading is affected by a range of factors, including the weather, fuel load and topography [5].

Only a few of critical variables for the fire-spreading model are directly measurable. For example, weather sensors provide us with air temperature, humidity, wind speed, and direction. Data accumulated in GIS make available information about a vegetation type, slope, aspect, and soil parameters.

The novelty of the proposed approach is that we not only estimate the spatial position of the fire front but using the remote sensing techniques, we can also indirectly obtain estimates of valuable parameters [14] that are necessary for the fire-spreading model:

- the combustion reaction intensity can be quantitatively estimated through the energy release available by the thermal infrared sensor;
- a fuel load can be qualitatively estimated through the analysis of vegetation density distribution associated with the certain vegetation type;
- a fuel moisture can be qualitatively estimated through the saturation and brightness analysis for a specific color (e.g., green);
- burnt areas can be qualitatively estimated through the contrast analysis (green-to-black).

During the monitoring mission, we need all above-mentioned estimations. These assessments allow decision-maker to calculate important fire parameters and make the prognosis of fire-spreading based on the approximate model.

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) [11].

Firstly, the terrain is divided into a finite set of disjoint spatial objects represented 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 be varried, so the terrain scale can be also changed.

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.

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.

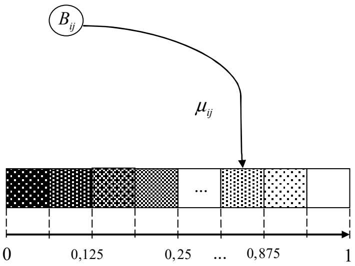

Fig. 3. Partial order of grey colors

For this, firstly we define the discriminating interval in RGB space *LG* = [RGB(60%, 60%, 60%) - RGB(95%, 95%, 95%)], which excludes 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.

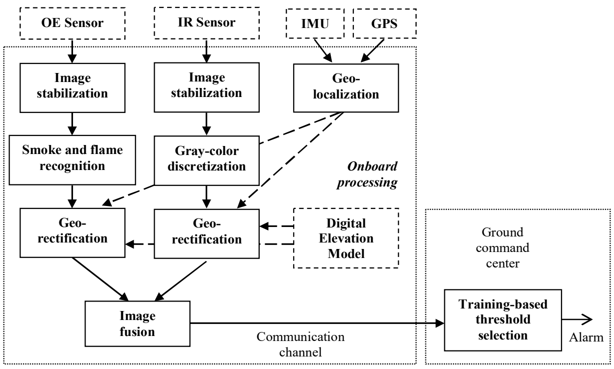

Fig. 4. Image processing during the patrol mission

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: $\upsilon_{ij} = \max(\mu_{ij}, \eta_{ij})$. Then the array of resulting values υ_{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 υ^*, we consider the fire detected only for the cells, which have greater or equal values of the ignition/burning possibility degree υ_{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 υ_{ij} can be considered as positive.

C. *Image Processing During the Monitoring Mission*

The monitoring mission is aimed at obtaining information about the fire features and behavior continuously. The monitoring UAVs should not be overloaded with substantial computing. UAV control system provides onboard only the image stabilization, geo-localization, and geo-rectification stages (Fig.5). The results are transmitted to the ground command center for further image processing since most of the processing is related to the color-chromatic analysis of images.

The weather sensors supply necessary information about air temperature and humidity, DEM provides sufficient information about the terrain, as well as the thermal infrared sensor supplies the model with the estimations of the fire intensity, which approximate the measured energy release of the combustion reaction. At the same time, the optical sensor provides us with information for the image processing, which starts from its transformation from RGB model to HSV model.

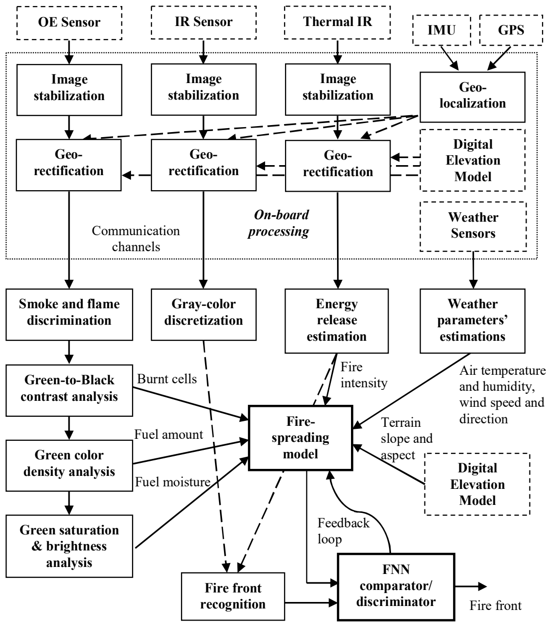

Fig. 5. Image processing during the monitoring mission

Using the HSV model, we perform a slice of the pixels of the green spectrum. Next, for each cell d_{ij} we evaluate the density of green pixels, using a partial order of green colors and implying the numerical green color density scale

$[\lambda_{\min}, \lambda_{\max}]$ by analogy with grey color as presented above. It gives us the estimation of the amount of the fuel within the cell. Finally, we estimate the saturation of all green pixels of the cell, which has a brightness more than 0,75. It gives us an estimate of the relative humidity on a scale of 0 to 1. As a result of image processing, we obtain all estimations of fuel-related parameters needed to predict the fire propagation speed and direction. Since the speed of the prediction is significantly limited by the image processing speed, this stage was transferred to the ground station.

Using the information from the infrared cameras, we can perform the fire front recognition. For example, the burnt cells can be discriminated by their color (close to black), as well as the burning cells can be discriminated by their level of radiation (temperature). Based on soft rough sets, the model represents the blurred fire front. It determines by a plurality of soft sets: a set of burnt cells, a set of burning cells, a set of possibly burning cells, and a set of free of fire cells. Therefore, the fire front is represented by the boundary region of the rough set of burning cells. Thus, at each moment we have two spatial descriptions of the fire front, the first is recognized as the result of infrared image processing, while the second is the result of the fire front prediction at the previous moment. Therefore, we can periodically compare the recognized fire front with the predicted one. It allows us to adjust the approximate model in order to improve the accuracy of the prediction. Good results in improving the model performance were obtained by the feedback loop through the Fuzzy Neuron Network (FNN). The accuracy of the prediction and the quality of the model as a whole can be easily estimated by detecting deviations between predictions and subsequent observations. Obviously, using the FNN feedback can significantly reduce those deviations. The ability of the developed system to work in near-real-time mode requires performing calculations based on the used fire-spreading model as quickly as possible because the time difference between the observation moment and the prediction moment should be small to neglect the influence of other factors.

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, and 1 octocopter for the monitoring mission). It used the approximate fire-spreading model [15] that allow calculating the rate of fire spread and obtaining the other fire parameters necessary for decision-making as well as the fire front location on the terrain map. All UAVs' cameras were precisely calibrated.

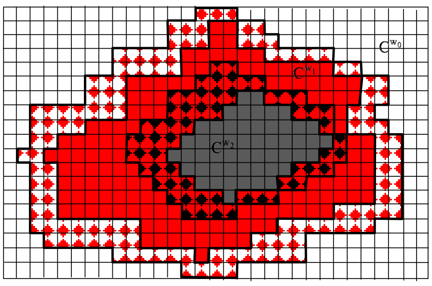

Fig. 6. Blurred fire front

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 (≈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 have 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

In the paper, the multi-UAV-based monitoring system for tactical forest fire-fighting operations is presented. The functions and missions of the system and its architecture are considered, UAV types and sensors are described. Remote sensing algorithms and image processing techniques are presented. The data integration into the fire-spreading model in the real-time DSS for the forest fire response is proposed.

The novelty of our approach is that we not only estimate the spatial position of the fire front but using the proposed remote sensing and image processing techniques we can indirectly obtain estimates of valuable parameters necessary for the fire-spreading model. This allows decision-maker to calculate important fire parameters and make the prognosis of fire based on the approximate fire-spreading model. Thus, 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 the fire prediction and response.

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