A Survey on Forest Fire Monitoring Using Unmanned Aerial Vehicles

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Abstract: Every year, forest fire causes heavy death toll and destruction around the world. The number of forest fires is increasing each year along with the damages associated with it. At this point, traditional forest fire detection methods such as point sensors, thermal sensors, watch tower, human patrol and satellite imagery are not being enough to provide early detection and continuous monitoring. Recent developments in electronics and control systems have made unmanned aerial vehicles (UAVs) more readily available and created an opportunity to utilize them for continuous forest monitoring with higher flexibility, maneuverability and precision. Early level experiments show that the limitations of the previous methods could be overcome by UAV-facilitated forest fire monitoring strategies. This paper highlights the basic idea of UAV-based forest fire monitoring and relevant researches and operations that have been conducted in this field thus far. The future of forest fire monitoring relies more on the use of UAVs and their onboard mission payloads, and the main motivation of this paper is to help for identifying the methodologies behind the existing systems and to find new methods of improving the UAV systems to fight this dreadful calamity.

Keywords: Unmanned aerial vehicle, forest fire monitoring, fire detection, smoke detection, image processing

1 INTRODUCTION

Forests provide important environmental and socio-economic support to mankind in the form of food, shelter, medicine, jobs etc. Forests keep the environment clean, climate balanced and our soil safe. They are safe havens for millions of different species who keep our ecosystem balanced. However, increasing occurrence of forest fire every year is threatening the wellbeing of our planet. Every year, wildfire across the globe is affecting almost three hundred thousand people, burning millions of hectares of lands, and costing billions of dollars out of the taxpayers' pockets [1]-[3]. In the long term, it is possible that forest fires will double the temperature of Earth's lower atmosphere [4]. A comprehensive report on the effects of wildfire suggests that it has affected 6 million people in the last 100 years, has a higher death risk than flood and a higher post-disaster expenditure than earthquake or flood [5]. The short-term and long-term effects of wildfire is causing the scientific community to look for methods of faster containment.

Before finding a method of early-stage detection, we have to understand the causes of wildfire. Wildfire is different from other natural disasters because it can be caused by both nature and human error. The natural causes of wildfire are lightning strikes, volcanic eruptions, rock sparks, surface level coal seams, powerlines, meteor impacts and spontaneous combustion. Human errors are usually uncontrollable prescribed burns, bonfires etc. There is no clear distinction in the primary cause of wildfire, human error or nature, but pattern suggests that in less densely populated areas, lightning is the primary cause of forest fire ignition while in more densely populated areas, human error is the main cause of forest fire [6]. With human activity increasing around the globe and drastic climate change, it is estimated that the occurrence of wildfire will increase 3-5 times within the next century [7]. It is almost impossible to pinpoint where forest fire will be ignited therefore taking preventative measures could be fruitless to reduce the effects of wildfire and the best course of action is to be able to detect it in an early stage and to provide continuous information to firefighters for faster containment and suppression [8].

Traditionally, forest fires have been detected using human patrol, smoke detectors, thermal sensors, watch towers equipped with optoelectric cameras, satellite imagery and manned aircraft [9]. Smoke and thermal sensors are point detectors requiring proximity to the fire and cannot provide information on the location or size of the fire [10]. Human patrols are affected by monotony and fatigue. Watch towers suffer from a limited field of view, lack of flexibility and high false alarm while satellite imageries have poor spatial and temporal resolution insufficient for early detection and continuous monitoring [9]. Additionally, these methods are insufficient to provide a real-time update to the firefighters for strategic and tactical planning.

Development in UAV technology lead more commercially available smaller and cheaper UAVs. While manned aircraft can confirm fire and provide real-time updates with full accuracy, it is extremely dangerous for the

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pilots [11]. Over the last 20 years, approximately 80 pilots have died in the USA during firefighting operations [12]. In contrast, UAVs can access high-risk zones, provide an over-the-hill view, perform night time missions with no risk of human lives. Furthermore, UAVs can hover over a spot, have high spatial and spectral resolution and they can provide continuous fire information to the firefighters for ideal suppression planning. These advantages of UAVs can overcome the limitations of traditional fire detection methods and have significant contribution in early detection and suppression of wildfire.

It is important to understand the methodologies and results of the existing UAV facilitated forest fire monitoring systems. This will enable a deeper understanding of the limitation in existing systems and find new algorithms to improve the results. This paper hopes to provide certain overview and guidelines to the current and future researches in this important field.

2 GENERAL UAV BASED FOREST FIRE MONITORING SYSTEM

The general methodology of UAV based forest fire monitoring is to use a single UAV or a fleet of cooperative UAVs fly over high-risk zones in a forest and capture images using their onboard optoelectronic sensors. The captured visual or infrared images will be processed on board or through a ground station for identifying the presence or absence of a fire. If a fire is confirmed then an alarm is sent to the nearby fire stations and personnel in charge along with the location and size of the fire. Figure 1 shows the three basic components of a UAV based forest fire monitoring system: vehicle, onboard sensors, and ground devices.

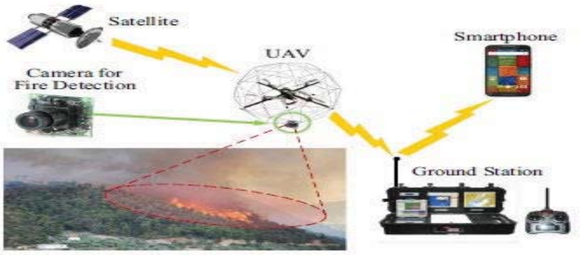

Fig. 1. A general view of UAV based forest fire monitoring system [13]

Depending on the aircraft type, UAVs can be classified as a fixed-wing or rotary-wing type [9]. Fixed-wing aircraft are cheaper, can carry a larger payload and can attain higher altitude and longer endurance. However, rotary-wing UAVs are more flexible, maneuverable and with the ability to hover, and easier for take-off and landing.

The payload attached to a UAV consists of sensors such as inertial measurement units (IMUs), GPS, visual camera, infrared camera and transmission-reception units. IMUs and GPS are useful to provide location information of the UAVs. Visual cameras and infrared cameras of different wavelengths are used to obtain images. The payload also consists of transmission and reception units such as antennas that allow communication among UAVs and between UAVs and ground station [14].

The ground station or decision support system (DSS) is a computer or laptop that maintains communication with the vehicles, receives information sent by the UAVs, processes the images, makes decisions and necessary computations and communicates with relevant authorities [14].

Choice of aircraft type or payload components depends on the type of mission that is taking place. In the presented literature, there are experiments and operations that used only rotary wing, only fixed wing or a combination of both types of aircraft. The same idea applies for sensors where there are reported experiments with just visual camera, just infrared camera or a combination of cameras. Finding the ideal combination of aircraft and sensor depends on mission duration, complexity and budget.

3 USE OF UAVS IN FOREST FIRE MONITORING OPERATIONS

During a firefighting operation, the area under effect can get seriously covered by smoke, leading to impaired vision, polluted air and hazardous conditions [15]. This makes it risky and difficult for firefighters and manned aircraft to assess the situation and make decisions quickly. UAVs can be deployed quickly and they can be used to capture images from low altitude and difficult positions for firefighters to understand the situation without putting their lives at risk [16]. Additionally, using UAVs have been proven to be the cheaper, more flexible and safer option when operating at close proximity of the fire [17], [18]. These factors combined with more readily available commercial UAVs have fueled more research in UAV based forest fire detection over the last two decades.

Although the first use of unmanned aircraft for forest fire monitoring was reported in 1961, it did not generate much interest until 1996 when a fixed-wing aircraft, Firebird 2001 carrying TV and FLIR camera, was used to aid firefighters in Montana, USA [11], [19]. A few years later, NASA Ames Research Center (NASA-ARC) and the United States Forest Service (USFS) conducted the First Response Experiment (FiRE) project using fixed-wing ALTUS II by carrying a four-channel multi-sensor payload [20]. The purpose of this experiment was to check the feasibility of incorporating UAVs into fire monitoring operations and they were able to achieve all the planned goals using the UAV.

Shortly after the initiation of the FiRE project, a group of researchers in the University of South Florida proposed a method of forest fire detection using UAVs and set up a small experiment that achieved 90% detection accuracy using their method [21]. The proposed method utilizes NIR/IR cameras but the method does not include the type of UAV they used.

Almost simultaneously, a large-scale project called COMET, funded by the European Commission, started researching on forest fire monitoring using unmanned system [22]. Over the years, their work expanded and became an operational system with three UAVs (two fixed-wing and one rotary-wing) carrying visual, infrared and fire sensors [23], [24]. The three UAVs work in collaboration with each other and they conducted numerous prescribed fire experiments to test the system's detection and monitoring capabilities.

The success of FiRE project influenced more research on forest fire monitoring using UAVs in the USA. In 2005, NASA-ARC used two fixed-wing and one rotary-wing UAVs in their premises to understand how UAVs can support firefighters during operations by capturing images of a small hotspot [11]. A year later, they conducted a day/night prescribed burn operation using four fixed-wing UAVs in Fort Liggett, California [11]. This successful operation observed UAVs sending real-time imagery to ground stations and informed the UAV community about the requirements of flying under forest fire scenarios.

In 2006, NASA-ARC developed Ikhana, a medium altitude long endurance UAV, to test the capability of this aircraft in long fire monitoring missions [11]. During 2006-2009, Ikhana provided almost real-time and orthorectified imagery of over 60 fires in the Western USA totaling 189 flying hours [11]. In 2008, US Department of Defense provided the RQ-4 Global Hawk UAV to provide imagery of the northern California fire in conjunction with the Ikhana [11].

USFS conducted more demonstrations on UAV based forest fire monitoring during 2009-2010. Two of these exercises were in conjunction with Association of Unmanned Vehicle Systems International, Naval Postgraduate School and US Army Dugway Proving Grounds [25]. USFS and US Army National Guard Maneuver Training Center collaborated to perform another UAV firefighting demonstration at Fort Pickett, Virginia in 2010 [20]. These demonstrations gave firefighters the opportunity to train UAV operators on directing sensors, maneuvering the UAVs accordingly, providing fire location, terrain features, etc. through these experiments, the UAVs demonstrated their capability of providing real-time information important to make strategic and tactical level decisions.

Another significant UAV based fire monitoring operation was conducted in Alaska by the University of Alaska Fairbanks. In 2009, a major fire broke out north of Fairbanks, Alaska in the Crazy Mountain Complex. The dangerous smoke cover forced manned aircraft to be grounded and the only way the fire progression could be tracked was by using the UAF ScanEagle UAV. The UAV was used to run operation through the smoke cover and provided imagery from complex and hazardous positions [20]. The University of Michigan in collaboration with US Airforce Research Laboratory used a 6 feet fixed-wing UAV equipped with an infrared camera and ran field tests under a heat-contrast environment to validate their proposed fire monitoring method [26].

To gain a better understanding of wildfire behavior, series of prescribed burns in the southeastern USA were conducted in 2008, 2011 and 2012 in a campaign called Prescribed Fire Combustion and Atmospheric Dynamics Research Experiment (RxCADRE) [27]. For these projects, fixed-wing (AeroVironment Raven, G2R and ScanEagle) and rotary-wing (Aeryon Scout) UAVs were used for data acquisition through visible and Longwave Infrared (LWIR) images [28]. Meteorological data such as air temperature, wind speed, wind direction, relative humidity and black carbon measurements along with the visual and infrared images collected in these projects allowed scientists to build better datasets and found new temporal and spatial fire patterns that can be used in future projects [27]. These missions also concluded that UAVs can be incorporated into firefighting missions without any major incidents [28]. Another experiment conducted in Western Virginia using Zephyr UAS demonstrated the advantage of using UAV in firefighting scenario [29].

Apart from the USA, several UAV based fire monitoring experiments were conducted in Europe. Szendo Fire Department in Croatia conducted 2 real fire experiments using UAVs in 2004 and 2005 where they concluded that infrared and red channel cameras provide enough information to the firefighters, 2-3 minutes of fire information is good enough to make tactical decisions, flight altitude of 500 meters is enough to provide useful information and that UAVs are very useful for forest fire monitoring [30]. The success of their experiments leads to the use of the first regulated UAV for wildfire support.

Esposito *et al.* [31] presented the preliminary results of an electro-optical payload consisting visible, near infrared and thermal infrared cameras attached to a fixed-wing mini UAV and applied for forest fire monitoring in Italy. This work, supported by the Italian Department of Space Science and Engineering, showed the capability of such a system in monitoring natural disasters.

Pastor *et al.* [15] describe a UAV based fire monitoring architecture developed with the support of the Ministry of Science and Education of Spain called "Sky-eye". They used an unmanned helicopter equipped with visual and thermal infrared cameras to provide fire and hotspot information to the ground station during the day/night operation. They concluded that using Sky-eye in fire suppression tasks is efficient because it reduces the number of resources that need to be allocated at the fire site.

The Dutch FireFly project used the Delftdynamics Robot Helicopter to provide firefighters real-time aerial video for fire suppression assistance through two exercised fire scenarios [32]. Although their experiments were not conducted under a wildfire scenario, they concluded that this method can be useful in other civil inspection purposes.

While all the experiments above were supported by the governments as part of a big project, recently there has been a surge of smaller scale, more independent researches in this field. In 2017, a series of laboratory experiments conducted in Concordia University, Canada used a fire simulator and a Qball X-4 quadrotor UAV equipped with visual and infrared cameras to develop a forest fire monitoring system [13], [33], [34]. Similar experiments were reported in [35] where they aimed at decreasing computation time and overall expense by only using the visual camera in their payload.

Along with more commercially available UAVs, newly developing machine learning algorithms have also garnered new interests in this field. A powerful new image classification tool called Convolutional Neural Network

(CNN) is being used heavily in recent researches [1], [36]-[39]. Lee *et al.* [1] conducted their experiment by burning small tree branches and using a smoke grenade to imitate forest fire scenario and captured videos of it using a UAV. Chen *et al*. [39] proposed a forest fire monitoring method and tested their framework using a six-rotor UAV and fire simulator. Zhao *et al*. [38] developed a forest monitoring fixed-wing UAV named PHECDA II but it has not been tested against any real or prescribed fire monitoring exercise thus far. In 2018, Wardihani *et al*. [40] conducted a prescribed fire experiment in Indonesia where they used a UAV equipped with an infrared sensor that flew over the prescribed burn zone and provided information in real time. In Ukraine, a forest fire monitoring framework was proposed and tested in a laboratory setup using a team of UAVs equipped with infrared and visual cameras [41].

From reviewing the existing literatures on UAV based forest fire monitoring systems, we can divide the term "monitoring" into three separate tasks: confirming the presence of fire, providing important information related to the existing fire and predicting future behavior for rapid containment and suppression. Additionally, depending on whether the systems are using a single UAV or a fleet of UAV, the overall framework changes. The following subsections provide some in-depth analysis based on each of these criteria.

3.1 Forest Fire Detection using UAVs

The first task of an ideal UAV assisted forest fire monitoring scheme involves patrolling potential high-risk zones. High-risk zones can be assessed through recent lightning, volcanic or human activities. Data acquired by the patrolling UAVs need to be assessed on board or by the ground station to determine the presence of fire. This phase of the monitoring task is known as "detection".

Merino *et al*. [23], [24] initially detected fire using a fire sensor and then confirmed this assessment using visual and infrared images. Their visual image used Gaussian smoothed color histogram in RGB color space and look-up table method described in [42] along with thresholding the infrared image. The detection scheme described in [21] thresholds infrared images to extract pixels with high intensity, measures the mean intensity and the size of the area and makes a decision using fuzzy logic rules. While these experiments only used static features of the flame, the systems described in [13] and [35] use both static and motion features by combining YCbCr color space rules with Lukas-Kanade optical flow method. The detection scheme proposed in [13] was further enhanced by adding infrared detection through Otsu segmentation [33] and fuzzy logic based smoke detection [34].

The CNN based detection scheme proposed in [1] trained their images with 5 different CNN models (AlexNet, GoogLeNet, Modified GoogLeNet, Modified VGG13 and VGG13) and their results showed 99% accuracy with GoogLeNet, however, the training time was 3.1 hours and classification time was 11.657 seconds. CNN model developed in [39] is capable of detecting both fire and smoke in the same frame but no actual result image was reported. The saliency detection method reported in [38] developed a flame detection CNN called Fire_Net. In their proposal, CNN is the last tool they use for classification preceded by Bayes-based saliency detection, extracting a Region Of Interest (ROI), creating a feature vector of the color moment, image energy and entropy from the ROI, and two logistic regression algorithms to classify flame and smoke. Their Fire_Net model outperformed AlexNet, Support Vector Machine (SVM), back propagation neural network and the CNN method proposed in [36]. Despite the high performance obtained in their method, the complexity of the algorithm makes it computationally expensive and experimental results from real life fire scenarios are desired. CNN based fire detection algorithms proposed in [36] and [37] used different variations of CNN to achieve very high accuracy results but their work was not tested with UAVs. However, aerial images were used in [36] and static images were used for training the CNN in [37] that indicates that these methods could be incorporated into a UAV based fire monitoring architecture.

The detection scheme proposed in [43] used image enhancement, block matching and support vector machine but it is yet to be tested in an experimental setup. Wardihani *et al*. [40] used an IR camera as a temperature to detect fire during their prescribed fire experiment. The method proposed in [41] used both infrared and visual camera for detection purpose. From the infrared image, they measured the mean intensity of each cell and computed different degrees of burning from 0 to 1. To avoid false alarms, the visual camera was used to detect smoke using a simple RGB threshold and then texture-based classification.

Cruz *et al*. [44] proposed a forest fire detection index (FFDI) where they modified an RGB image to enhance the tonalities of flame and smoke to achieve a precision rate of almost 97%. Future experiments in this field can use their FFDI for fire and smoke detection and validate their results.

3.2 Diagnosis of Identified Fire

Once the fire has been confirmed by the UAVs, the next task is to provide important initial information to firefighters and relevant authorities, namely the location and the size of the fire. UAVs are usually equipped IMU and GPS sensors that allow ground stations to estimate fire locations and UAVs' positions. However, these sensors are not enough to provide completely reliable information on the location(s) of the fire(s) because depending on the height and terrain type, the identified fire pixels could be located anywhere in the field of view of the UAVs [45]. One of the most common methods of providing geolocation is applying homography on an existing Digital Elevation Map (DEM) of the area under surveillance. This method was reported in [15], [24], [41] and [46] for providing accurate geolocation. Another popular method of providing geolocation is orthorectification and mosaicking reported in [26], [32] and [47]. Apart from these methods, Wardihani *et al*. [40] used their IMU and GPS to provide a real-time location to almost perfect accuracy.

3.3 Predicting Fire Behavior - Prognosis

The final task of a UAV based fire monitoring system is to provide continuous information about the fire to firefighters and aid them in making strategic and tactical decisions for rapid containment and suppression. This involves tracking the active fire line, estimating the rate of spread and predicting the direction of propagation. In the presented literature, only a handful of proposals involve predicting fire behavior. Merino *et al*. [23] estimated propagation direction using a grid-based probability model which estimated the probability of fire spreading to the surrounding grids. Their work also involved using an infrared camera to extract the baseline of the fire. The method presented in [26] proposed that from the infrared images they captured, it is possible to estimate the active fire zone and track it. In [41], the authors reported achieving 96% accuracy in predicting fire behavior under different terrain and weather conditions.

3.4 Cooperative UAVs for Forest Fire Monitoring

It is not reliable enough to depend on a single UAV for fire monitoring tasks. Forests cover a large area, wildfire can spread for miles and the UAVs can fall victim to electrical and mechanical faults. Therefore, for a complete system that can provide continuous monitoring reliably, it is better to have a team of UAVs working in collaboration. A simulation-based experiment conducted showed that a team of six UAVs can provide information with minimum latency patrolling around the fire perimeter [48]. A few more cooperative UAVs model optimized for wildfire fighting have been proposed in [49]-[53] that were all validated using simulations. A series of laboratory experiments conducted in Concordia University, Canada implemented its model with Qball X-4 quadrotors. Their initial work was a formation setup upon detecting fire using a leader-follower model [54]. Later, they expanded their model by adding Fault-Tolerant Cooperative Control (FTCC) strategies to their framework where the constant communication UAVs will be able to identify if one of the vehicles in the team is experiencing a fault or requires refueling and will change their formation accordingly. The experiment reported in [41] used three cooperating drones for patrolling mission and a helicopter for fire confirmation. The only cooperating UAV fleet in a field scenario has been reported in [23] with two fixed-wing aircraft and a helicopter working in constant communication with each other. Recently, a cooperative unmanned aerial and ground vehicle for wildfire monitoring framework was proposed but it is still in the proposal stage and no simulation or laboratory experiment has been conducted thus far [45].

4 CONCLUSION

An unmanned aerial vehicle facilitates wildfire monitoring system, detects fire faster, provides imagery from complex locations, makes operations safer and saves lives. This survey shows that UAV-based forest fire monitoring is an active area of research and there is plenty of rooms to improve the existing systems. The UAVs are becoming cheaper by the day and they are being equipped with stronger on-board processors and sensors. Algorithms that scientists could not implement in UAV based operations previously could be incorporated now, opening up new fields in this research.

This review paper provides an in-depth survey on the fire detection, diagnosis and prognosis algorithms used by the existing systems and makes it evident that there is still a lot of rooms to improve the algorithms. Out of all the literature presented, only a couple of the existing systems complete all three tasks of fire surveillance. Newly developing detection algorithms along with traditional machine learning algorithms such as neural networks, support vector machine etc. can be incorporated in new systems and must be tested under a wide variety of scenarios to validate their robustness. Ideas can be taken from existing fire behavior prediction models and implemented into UAV systems to understand their capabilities.

A clear gap in consistency is evident in the existing detection methods in terms of performance. Every proposed algorithm has used its own database and performance measurement methods to evaluate their systems. Future work in this field can also include creating a common database available for the public and evaluate each algorithm with a consistent performance metric in terms of recall, precision and computation time etc. Another limitation of all existing system is that none of them were used in a real scenario where the UAVs might not find a fire for days, as fire is a relatively rare phenomenon in nature. How an existing system will perform in such scenarios is yet unknown.

Computer vision wildfire monitoring facilitated by UAVs can overcome all the limitations of the existing watch tower, human patrol, manned aircraft and satellite methods. With current technology, it is more possible than ever before to create a robust UAV based forest fire monitoring model that can be implemented in a real-life scenario. The overview provided in this survey can be used as a guide for all future works in this field to identify the strong points and limitations of the existing systems so that further improvements can be implemented on them.

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