International Journal of Earth, Energy and Environmental Sciences
ISSN: 2517-942X
Vol:14, No:11, 2020

Application of UAS in Forest Firefighting for Detecting Ignitions and 3D Fuel Volume Estimation

Artur Krukowski, Emmanouela Vogiatzaki

***Abstract*—**The article presents results from the AF3 project "Advanced Forest Fire Fighting" focused on Unmanned Aircraft Systems (UAS)-based 3D surveillance and 3D area mapping using high-resolution photogrammetric methods from multispectral imaging, also taking advantage of the 3D scanning techniques from the SCAN4RECO project. We also present a proprietary embedded sensor system used for the detection of fire ignitions in the forest using near-infrared based scanner with weight and form factors allowing it to be easily deployed on standard commercial micro-UAVs, such as DJI Inspire or Mavic. Results from real-life pilot trials in Greece, Spain, and Israel demonstrated added-value in the use of UAS for precise and reliable detection of forest fires, as well as high-resolution 3D aerial modeling for accurate quantification of human resources and equipment required for firefighting.

***Keywords*—**Forest wildfires, fuel volume estimation, 3D modeling, UAV, surveillance, firefighting, ignition detectors.

I. Introduction

WILD forest firefighting commonly depends on operational data acquired by firefighters from visual observations. Such estimations are subject to various errors and inaccuracies due to smoke obstructing the flames, human inability to perform visual estimation and errors in the identification of fire location. Various modern technologies have been applied to firefighting over recent years helping to resolve such problems. However, many of these still have suffer from practical problems in operational conditions, such as low reliability and accuracy, excessive costs and other ones. UAS can play a key role for forest fire response [1]. They have been already successfully demonstrated in the past for fire detection, localization and observation [2], [3]. Fire monitoring is generally related to real-time analysis of the evolution of the most important parameters related to fire propagation, including shape and position of the fire front, its evolution in time and the average height of the flames [4]. When integrated within a Geographical Information System (GIS), such information can be leveraged for more efficient deployment of firefighting resources, being the core of its use in the presented AF3 project.

The AF3 project enhanced fire detection and monitoring systems' capabilities, integrating traditional and alternative means of observation and exploiting sensor, surveillance and other relevant technologies beyond the state of the art. For this purpose, a wide array of sensors was deployed including satellite, airborne as well as ground mobile and stationary systems, with monitoring and detection data being fused, managed and visualized into an integrated environment. In AF3, an additional essential objective was the seamless capability of monitoring and fire detection through all fire development phases as well as during post-fire and pre-fire phases, also beyond fire categories (interface fires). In such a system, the UAVs play an important role for early detection of fire ignitions and validation of fire alerts by performing both visual and sensor-based verification of the actual incidents. During firefighting, combined with unmanned ground vehicles they support close range surveillance of firefighting operations, search and rescue as well as on the spot analysis of situation at the fire front. After incidents, they can be used to survey the area in search for re-ignitions, assess damages to infrastructures, livestock as well as search for possible casualties and survivors.

The concept of its operation is based on detecting changes in near-infrared spectrum corresponding to significant changes to ionized potassium and oxygen levels. The sensor uses a commercial STS-NIR micro spectrometer with either Raspberry PI revision 3 or Raspberry PI-Zero-W 1.3 used to host acquisition software and an on-board WEB server used for transmitting the measurements as well as alerts to C4I. Additional multi-constellation GPS receiver was added to the RASPI device to allow for precise positioning of incident areas without depending on the UAV positioning system. This way the device can be effortlessly deployed on any other flying or ground vehicle. The weight of the sensor node including spectrometer and rechargeable 2300 mAh battery does not exceed 300 grams (1st version) with the latest release lighter than 100 grams, allowing more than 4 to 6 hours of continuous operation. The real-life validation tests in Athens and in Spain have confirmed initial expectations and the anticipated performance of the sensor when used both on ground and on board of the DJI Inspire 1 and DJI Matrix UAV platforms.

II. NIR Spectroscopy for Detection of Fire Ignitions

Embedded NIR spectrometer deployed either on ground or aerial vehicles can be used for close-range monitoring of temporal changes in the atmospheric oxygen absorption and ionized potassium over forest fire areas for detection of possible (re-)ignitions of the biomass. As shown in Fig. 1, there are number of characteristic features that can be detected in the NIR spectrum for forest fires.

The easiest way to detect biomass fires have proven to be potassium emissions [5] (double peaking in the NIR spectrum

Artur Krukowski, PhD is with the Research for Science Art and Technology (RFSAT) Limited, Dublin, Ireland (e-mail: Artur.Krukowski@rfsat.com).

Emmanouela Vogiatzaki, PhD is with the University of the Peloponnese, Nafplio, Greece (e-mail: Emmanouela@rfsat.com).

at 767.4 nm and 770.7 nm) with additional oxygen absorption, as shown in Fig. 1, the former one appearing more significantly than the latter one, hence it has been adopted in the test system for indicating a possibility of a biomass fire. When deployed on autonomous UAVs, this can be combined with imaging in both visual and thermal surveillance, thus providing visual confirmation of a potential incident. The same images can be also used for 3D modeling and volumetric fuel estimation of the biomass in the given area, as well as post-incident damage analysis, as it is described in the next section.

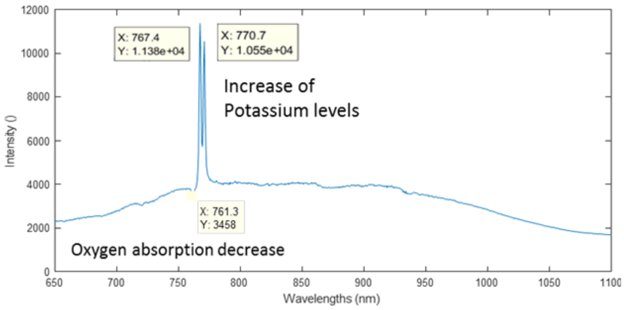


Fig. 1 Sample of measured data from NIR spectrometer during tests in Athens

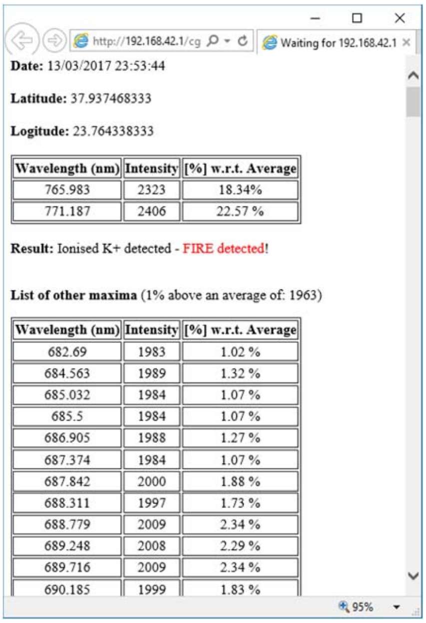
In the AF3 project, the NSTS-NIR spectrometer from Ocean Optics [6] covering the range of 650-1100 nm has been used, which delivers sufficient performance and accuracy in performing low-concentration absorbance measurements for forest fire detection. Its rugged design with small weight (50 g) and size (4x4x3 cm) makes this sensor a very attractive option for deployment on micro-UAVs that cannot lift heavy payloads, not to mention also its small footprint. In the test design (Fig. 2), an STS Developers Kit has been used that integrates an STS-NIR spectrometer, Raspberry Pi microcomputer, as well as customizable software with wireless networking. This allowed deploying the complete system without much additional development. By adding a Wi-Fi on a USB, the Raspberry could be used as a WEB server this allowing to provide measurements both in real-time for remote clients on the ground and for storing on an embedded SD memory.

Fig. 2 The fire detection sensor on PI-Zero W mounted on DJI Mavic

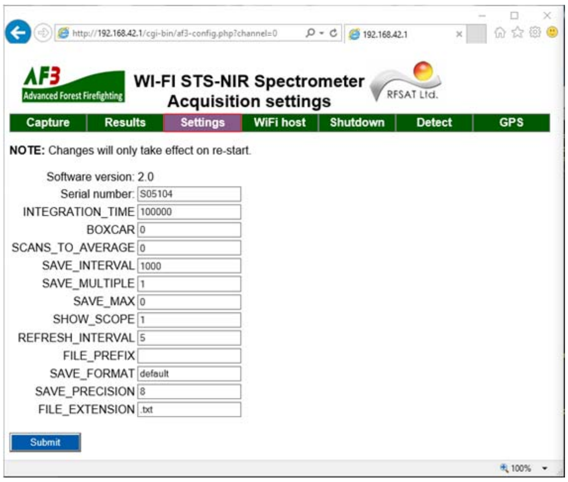
The latest version of the fire detection sensor is presented in Fig. 2. It is a modification of the original STS-NIR Development Kit from Ocean Optics, where extra NIR camera and GPS receiver were added to allow geolocated sensor measurements with visual confirmation. Since the original design on RASPI-3 was quite bulky, a custom deployment on a Raspberry PI Zero Revision W has been made to lower the size and weight of the entire system, thus making it small enough for deployment on smaller types of drone, such as DJI Mavic Pro. The latter version includes an embedded Wi-Fi interface to allow both remote configurability of the sensor node and permitting direct pull of sensor data in real time from the spectrometer, subject to client devices not exceeding maximum range of 300 meters in line of sight. If the distance is exceeded the data from the sensor can be stored on the onboard SD memory card for post processing on return of the UAV to base. To further reduce the weight, the rechargeable battery from the first version of the sensor node has been be replaced with a custom DC-DC downconverter to allow drawing the power to the sensor from the onboard battery of the UAV. In the subsequent version, the GPS received will be integrated directly onto GPIO pins of the RASPI-Zero-W while current off-the-shelf USB connectors will be replaced with direct ribbon cables, thus lowering the overall weight to a minimum. Such an approach will also allow deploying sensors on any type of commercial or custom drone.

In the first version of the sensor, the total weight including the spectrometer and the rechargeable 2300 mAh battery does not exceed 300 grams; while in the latest release the total weight does not exceed 100 grams. The overall weight of the sensor has a direct impact on the total flying time of the drone. It has been established that while the first version may reduce the total flying time of the drone by nearly 8 minutes, the latest version does not reduce it more than 2-3 minutes, under the same environmental conditions (e.g. wind speed). Measurements were made by placing both sensors on two UAV of same type and lifting them 10 meters above the ground, few meters apart.

An important part of the whole design is an embedded WEB server built upon the SDK from Ocean Optics. The development Kit came with a demo software that included the most important features such as capture, configuration and data transfer, written in PHP, and accessible remotely via on-board WEB server. This requires clients to make direct connection to the drone for accessing NIR sensor information. Custom adaptations included additional configurations, peak-based waveform analysis for determining existence of potassium emission with oxygen absorption for creating fire alerts, as well as geolocation of the measurements independently from GPS used by the UAV. Screenshots from the embedded WEB server are shown in Fig. 3. They include fire detector screen with list of peaks detected at various frequencies at a given location, Fig. 3 (a) and original configuration page, Fig. 3 (b). The original software from Ocean Optics allows also for real-time monitoring of spectrum e.g. during the flight, while measurements are saved on the memory card for possible processing at the control center, if required. By allowing custom filtering and wide range of observation times (integration period), the sensitivity can be increased that might be useful for e.g. surveillance from higher altitudes and/or larger distances, at a price of a lower flight speed.



(a)



(b)

Fig. 3 Screenshots from the embedded WEB server for accessing real-time spectrometer data from micro-UAV: (a) fire alerts based on finding potassium maxima, (b) WEB application for NIR spectrum capture

III. UAV-Based 3D Modeling of Fuel Volume and Surveillance of Large Areas

Images acquired from UAVs and especially from micro-UAVs can be used to create 3D maps of the area to allow e.g. estimation of forestation and especially volume of areas under tree canopies corresponding to the amount of potential flammable material, identification of urban areas and for damage analysis after the incidents, being its main purpose in the AF3 project. Such images need to be taken using specially designed fly paths and hence preferably automatic flight routes need to be used, although it is also possible to perform manual fly byes if full area coverage is performed.

Diverse types of software have been used to produce 3D models of the areas, including Pix4D Mapper [7], Autodesk ReMake [8], Agisoft Photoscan [9] and Artec 3D Studio [10]. The first one proved to be most versatile and offering options for highest accuracy especially when combined with the Pix4D Capture [11] software running on the Android and/or iOS-based platforms to perform autonomous fly-overs above the areas of interest. Images captured automatically can be processed either online by uploading them to the Pix4D online server for processing, or off-line on a custom PC workstation to produce 3D models in formats suitable for visualization on the C4I (e.g. 3D-PDF, KLM etc.) and/or subsequent processing (e.g. OBJ, etc.). Since processing of 3D models is a very computationally intensive process, this cannot be performed real-time, especially when high resolution is required. Typical processing time on a quad-core 2.7 GHz I7 Intel processor takes approximately 3-4 hours or more, depending on the number of images and complicated areas, reaching even days on slower workstations and/or when pushing the limits of the photogrammetric technology e.g. for centimeter accuracies from altitudes of 30 meters or above. Hence, such models would be most applicable for advance surveillance of the forest areas and in crisis situations e.g. for assessment of damages during recovery. During firefighting, its applicability might be decreased due to smoke, dust and air turbulences that might affect the visibility and precise positioning of the UAV platforms over the surveyed areas. In such cases, the 3D models can be also built from images captures from e.g. thermal cameras that can penetrate the smoke and to some level also the first canopies. Examples of both types of models were produced in the AF3 project. Two trials have already taken place in the project, one in Greece at Scaramanga naval base near Athens. During those tests, visual imaging has been made in both urban and mountain areas using DJI inspire 1 to perform comparative tests of 3D modeling performance with diverse flying paths. Results for urban area are shown in Fig. 4. In this test, regular grid has been made with UAV performing fully autonomous image capture, stopping at each capture location (left) resulting in highly precise representation of the area of interest (right) down to detailed car models. In this test, images were taken from an altitude of 30 meters using DJI X3 camera (HD resolution).

Additional tests in Athens trials were made in the nearby mountain area to test the accuracy of the 3D models (Fig. 5). Similar fully autonomous image capture from altitude of 30 meters was used with same DJI X3 camera over a dense three-path grid. Significantly more images were captured (204 as compared to 30 from previous test), which resulted in much more accurate representation of ground features down to individual branches clearly visible on the stacks of wood used for target practice. This allowed for very precise (5-10% accuracy) volumetric analysis of the amount of wood placed at each target, as shown on the right in Fig. 5.

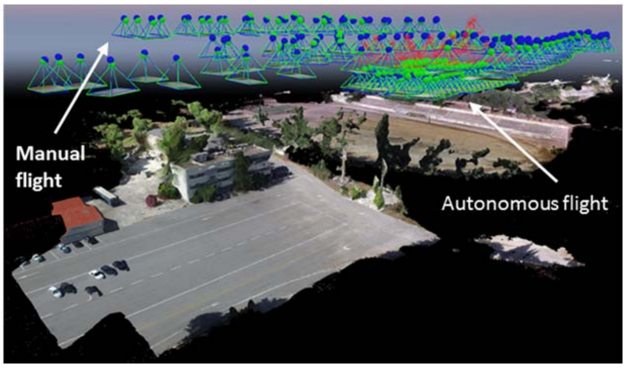


Fig. 4 Trials in Athens: complete 3D model for Test Area #1

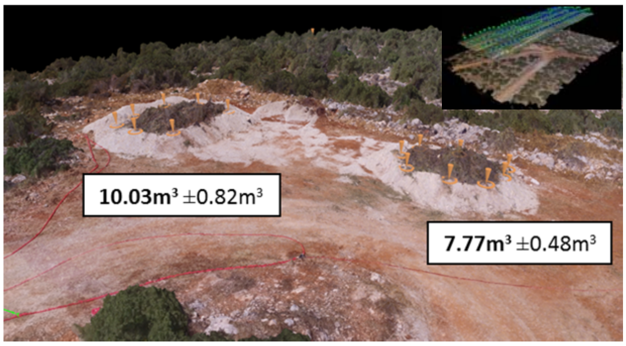


Fig. 5 Trials in Athens: 195x40-meter area with fly paths (left) and 3D volume analysis for Test Area #5

Second trials of the AF3 project took place in Leon, Spain. During those tests both visual and thermal images were captured, from which 3D models were produced. In those tests, manual UAV operations were performed (irregular grid and/or single corridor) to validate the possibilities of building models from both regular and irregular observations. The same area has been scanned multiple times using either visual (20MP) or thermal (640x480 pixels) camera. Using different types of cameras with diverse resolutions allowed also to verify the compromise between the resolution, the number of images and the density of image captures (overlap). In all those tests the drone did NOT stop when capturing images. The results of 3D modeling are shown in Fig. 6.

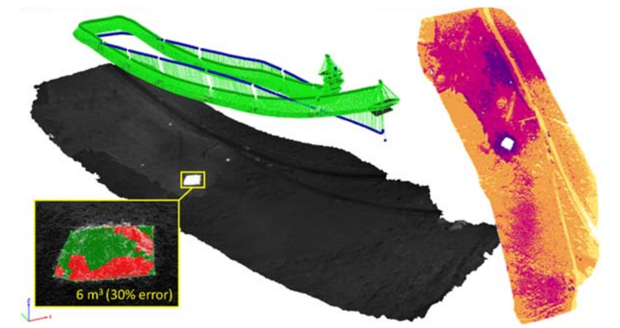


Fig. 6 Models of test area from UAV observation during test trials in Leon: result from 2060 low-res (640x480) FLIR images

The image capture strategy adopted during trials in Spain has demonstrated clearly negative effects of performing non-structured image captures on the accuracy of final 3D model. From one side, it has proven that regular grid along multiple corridors can offer high resolution and accuracy, whereby accurate representations of individual vehicles can be produced as well as fire front and targets well defined with only 22 images taken. On the other hand, thermal images were taken very densely (nearly 3000 images over 200-meter long area), considering their low-resolution. However, no attention was paid to the camera orientation (forward looking) without stopping for images capture. Hence, although the high density of images allowed for accurate representation of ground details (right in Fig. 6), sufficient for assessing biomass content to 30% accuracy, the bending of the UAV nose down when moving forward (similarly to helicopters) has caused false ground bending in the resulting 3D model, since such information is not included with camera parameters (only viewpoint with respect to the drone body is registered). This requires either post processing to flatten the ground or the a-priori knowledge of the drone bending during flight. The latter one is dependent on the drone and its speed and hence could be easily compensated for during 3D model processing.

Fig. 7 Models of test area from UAV during test trials in Israel (April 2017): using images from DJI Mavic Pro

The third and last trials have been conducted in Ashkelon in Israel and coordinated by ELBIT Systems. Two UAV flights have been performed, one using commercial DJI Mavic Pro UAV at the height of 10 meters in four corridors and lasting only 5 minutes, while the other one was made by Skylark 1 produced by ELBIT Systems, from the height of 100 meters, which circled around the test area for half an hour. The 3D models have been produced from both UAVs, which are shown in Fig. 7. As expected, the low altitude flight along regular corridors resulted in a very accurate 3D model, thus allowing to determine the volume of the wood at the target area with accuracy of 0.5%, better than during trails in Athens where accuracy was about 6-8%. However, the models from Skylark 1 have resulted in a very poor model, showing excess errors in discrimination of heights. This was clearly a result of images being taken along a narrow cone path over the target area, i.e. exhibiting small angular separation. This is analogous to achieving poor height determination in GNSS system for closely positioned satellites.

Considering that 3D model generation using photogrammetry may lead to extensively long processing times, investigation of speeding up the processing using custom built workstation has been conducted. To achieve a working compromise between computational performance and the overall cost of the system, the coprocessing with CUDA parallel computing platform and programming model invented by NVIDIA [12] has been adopted. CUDA cores have long been suggested for coprocessing of simple fixed-point operations like those required by the 3D modeling. The latest cards from NVidia [13], such as GeForce GTX 1080 (TI) and Titan X include large number of CUDA cores, 2560 and 3584, respectively. Hence, a custom workstation has been built that uses 3.6 GHz 8-core Intel-I7 processor with 32 Mbytes of RAM and dual NVidia GeForce GTX 1080 cards, i.e. adding a total of 5120 CUDA cores, total cost closing at 3000 Euros. Such an approach allowed for speeding up 3D model processing more than double for the same size of the project. Encouraged by those results, consideration is made for building the second version of the workstation with dual Intel-I7 processor server board and quad NVidia GTX Titan X graphics cards (connected internally via 4-slot SLI bridge), i.e. adding 14336 CUDA cores in total. This is expected to increase the current processing speed almost five times more, in practical terms allowing to produce high-res 3D models currently needing 16 hours in under an hour in ultimate quality, while only needing tens of minutes for near-real-time surveillance purposes.

IV. Conclusions

In this article, the results of research and development in the areas of UAV based forest fire detection using NIR spectrometers, visual and thermal surveillance leading to 3D photogrammetric modeling of areas of interest performed in the AF3 project were presented along with analysis of data captured during two real-life forest firefighting trials. The NIR spectrometer design based on the Raspberry PI Zero microcomputer, with size and weight suitable for deployment on micro-UAVs such as DJI Mavic Pro and Inspire 1 has been presented. Such sensors have proven to provide accurate detection of biomass burns from distances of tens of meters (sensitivity depending on the selected integration time) making them suitable for automatic detection of ignitions and/or fires hidden under canopies and obstacles and hence less likely to be detected by on-board cameras either visual or thermal ones, especially when used for detection of possible re-ignitions due to raised ambient temperatures post firefighting. Both real-time access to sensor data via WEB server embedded into the sensor node and possibility to offload raw measurements on return to base offer opportunities for real-time surveillance and precise analysis of condition of surveyed areas from control centers.

The performance of the sensor node has been verified in Athens trials showing sufficient sensitivity from tens of meters. The models based on a set of images taken by UAV's HD-resolution camera during 10-minute flyby over a 1000 square meter area at an altitude of 40 meters was such that shapes of individual tree branches with sizes below 2 centimeters could be clearly seen in the model featuring over 100-million-point cloud and 10 million faces. Furthermore, thermal images of same areas were captured with 640x480 resolution FLIR camera. The 3D models resulting from those images have been processed and are also presented here in. An embedded sensor device has been developed, aimed for mounting on a micro-UAV for detecting fire ignitions, with first version fitted onto DJI Inspire 1, while a reduced version was developed for a smaller DJI Mavic Pro.

The concept of its operation was based on detecting changes in near-infrared spectrum corresponding to significant changes to ionized potassium and oxygen levels. The sensor uses a commercial STS-NIR micro spectrometer with either Raspberry PI revision 3 of PI-Zero 1.3 used to host acquisition software and an on-board WEB server used for transmitting the measurements as well as alerts to the C4I. Additional multi-constellation GPS receiver was added to the RASPI device to allow for precise positioning of incident areas without depending on the UAV positioning system. This way the device can be effortlessly deployed on any other flying or ground vehicle. The weight of the sensor node including spectrometer and rechargeable 2300 mAh battery does not exceed 300 grams (1st version) with the latest release not exceeding 100 grams, allowing more than 4 to 6 hours of continuous operation.

The article also presented the usage of images and videos that could be captured by UAVs during their aerial operations as short as few minutes over wide areas of interest for highly precise (down to centimeters) 3D modeling of the environment, allowing for precise assessment of the burning biomass. Various strategies for surveying the areas, from regular grids to free hand flybys, have been discussed with respect to their effect on the accuracy of the achieved models. It has been determined that to avoid false ground bending, images should be captured when UAV is stationary, while highest accuracy can be achieved when regular grids along multiple corridors are used with image overlap over 50%. In such cases observations from altitudes of 30 meters using HD cameras may reach accuracies of single centimeters (subject to favorable weather conditions). Comparisons between high and low-resolution cameras have been also discussed along with analysis of the compromise with number of images and their respective overlap. This has been demonstrated by comparing small number of high-resolution images to large number of low-resolution ones over the same area. It has shown that both approaches may result in similar quality of 3D models, although processing time is significantly longer with the increase of the number of images. Means of speeding up processing by CUDA based coprocessing have been investigated, showing a significant decrease of the processing times as compared to computations made by main processor only. Use of dual NVidia GeForce GTX 1080 graphics cards with 2560 cores each allowed for the reduction of the overall processing time more than twice for the same types of projects. Real-life validation tests confirmed initial expectations and the anticipated performance of the sensor when used both on ground and on board of the DJI Inspire 1 and DJI Matrix UAV platforms. Further work on the reduction of sensor size and weight, increasing 3D modeling speed and accuracy as well as autonomous UAV operations was conducted and evaluated during real-life firefighting trials in Israel. They allowed producing even more accurate maps of fire test areas with precise assessment of the fuel volumes of the targets. The final tests in Israel also included swarm operation and real-time streaming of information from micro-drones, which could be controlled either locally or from a Ground Station integrated into Remote Control Center and overall incident Mission Control.

Results of this work have been presented to the Community of Users (EU firemen organizations) at the UAV Workshop and have been received with much interest and anticipation for deployment in future operational forest wildfire conditions [14].

Acknowledgment

The research leading to these results has been partially funded by the European Union Seventh Framework Program (FP7-SEC) under Grant Agreement N° 607276: AF3 “Advanced Forest Firefighting” and from the Reflective Societies program of the Horizon’2020 Research Framework under Grant Agreement N° 665091: SCAN4RECO. Authors would like also thank University of Westminster, London (UK) for co-funding of this work via subcontracting agreement under AF3 project.

References

[1] ISO 16730-1:2015 - Fire safety engineering: Procedures & requirements for verification and validation of calculation methods. Part 1: General: http://www.iso.org/iso/home/store/catalogue_tc/catalogue_detail.htm?csnumber=62111
[2] Ambrosia, V., Wegener, S., Sullivan, D., Buechel, S., Brass, S. D. J., Stoneburner, J., and Schoenung, S. (2003) “Demonstrating UAV-Acquired Real-Time Thermal Data over Fires”. Photogrammetric Engineering and Remote Sensing, 69(4):391–402.
[3] Merino, L., Caballero, F., Martínez de Dios, J., Ferruz, J., and Ollero, A. (2006) “A cooperative perception system for multiple UAVs: Application to automatic detection of forest fires”. Journal of Field Robotics, 23(3-4):165–184.
[4] Viegas, D. X., Cruz, M., Ribeiro, L., Silva, A., Ollero, A., Arrue, B., Martínez de Dios, J., Gómez-Rodríguez, F., Merino, L., Miranda, A., and Santos, P. (2002) “Gestosa fire spread experiments”. Proceedings of the IV International Congress on Forest Fire Research (ICFFR), pp. 1–13, Coimbra, Portugal.
[5] Vodacek A. et al (2001) “Spectral Features of Biomass Fires”. Digital Imaging and Remote Sensing Laboratory. https://www.cis.rit.edu/~rlkpci/PDFs/OPTONe_SPectral.PDF
[6] STS-NIR SDK: https://oceanoptics.com/product/sts-developers-kit
[7] Pix4D Mapper Pro: https://pix4d.com/product/pix4dmapper-pro
[8] Autodesk ReMake: https://remake.autodesk.com
[9] Agisoft Photoscan: http://www.agisoft.com
[10] ArTec 3D Studio: https://www.artec3d.com/3d-software/artec-studio
[11] Pix4D Capture: https://pix4d.com/product/pix4dcapture
[12] CUDA: http://www.nvidia.com/object/cuda_home_new.html
[13] NVidia GeForce: https://www.nvidia.com/en-us/geforce/products
[14] Artur Krukowski and Emmanouela Vogiatzaki, „ UAV-based photogrammetric 3D modeling and surveillance of forest wildfires”, Workshop on “UAV & SAR: using drones in rescue operations”, ISA, Rome (Italy), 29th of March 2017.