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Songsheng Li

Abstract: Wildfires erupt annually around the world causing serious loss of life and property damage. Despite the rapid progress of science and technology, there are no effective means to forecast wildfires. Various wildfire monitoring systems are deployed in different countries, most depend on photos or videos to identify features of wildfire after the first outbreak, while the delay of confirmation varies with technology. An autonomous forest wildfire early warning system is presented in this paper, which employs the state-of-the-art Unmanned Aerial Vehicle (UAV) to fly around a forest regularly according to established routes and strict procedures, to collect environmental data from sensors installed on trees, to monitor and predict wildfire, then provide early warning before eruption if a danger emerges. Bluetooth Low Energy (BLE) is employed to exchange data between UAV and the host of sensors. The collected monitoring data such as temperature and humidity is effective to reflect the real condition of the forest, which could result in the early warning of wildfires. The application of this system in the environment will enhance the ability of wildfire prediction for the community.

Key words: Bluetooth, Early warning, Forest, Sensor, Unmanned Aerial Vehicle, Wildfire.

1. Introduction

Autonomous forest patrolling is a classical topic of research as forests covered almost 31% of the planet land surface in 2012, according to the Earth Policy Institute from Rutgers University (Adams 2012). Surveillance of forests is difficult as they are too vast for humans to cover them evenly. Wildfires erupt annually around the world causing serious loss of life and property. The situation is worsening although the rapid progress of science and technology seeks to alleviate the problem. Modern inventions, such as digital cameras, airplanes and robots, open an automated possibility of forest exploration and surveillance. Satellites (ESRI 2017) are employed to monitor wildfire too, but they only provide visual information after burning. Environmental parameters of the forest should be collected and ana-

Abbreviations: UAV: Unmanned Aerial Vehicle BLE: Bluetooth Low Energy WSN: Wireless Sensor Network OP: Observation points BLEDC: BLE data collector BLEDA: BLE data agent POI: Point of Interest UUID: Universally Unique Identifier ISM: industrial, scientific and medical advInterval: Advertising interval advDelay: advertising delay NVM: non-volatile memory MHI: Minimal Human Intervention

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lyzed, then the corresponding early warning could be provided in real-time, which is similar with the ubiquitous building monitoring system.

In this paper, a forest patrol and wildfire early warning system is proposed, implemented by employing Unmanned Aerial Vehicles (UAV), wireless sensors and Bluetooth Low Energy (BLE). Observation points (OP) are distributed in the forest with a BLE data collector (BLEDC), their locations are marked during installation. UAV with a BLE data agent (BLEDA) acts as a central mobile station, flying to OPs according to their locations, collecting data from peripherals which are BLEDCs in OPs, then flies back to the station where the collected data is uploaded and analyzed, with an early warning delivered as necessary; the UAV flies periodically on schedule. Communication between BLEDC and BLEDA is BLE, designed to reduce power consumption and relative cost. This paper focuses on the hardware and working flow of the system.

The advantage of the proposed system is its low-cost, applicability and effectiveness. Fierce competition in the consumer market of UAVs has made these devices much cheaper, more reliable and more capable than ever before. The advanced feature of UAV in the proposed system is the Intelligent Flight Mode (DJI 2017), which has been implemented in a general consumer product, to make it affordable for a small community or local council to apply the system to protect residents and natural resources. A disadvantage of the system is the difficulty of deployment, installation and maintenance as BLEDC is installed on the tree.

An explanation of the proposed autonomous forest patrol and wildfire early warning system is described, then the test results are presented and a comparison with other systems in use is offered. Finally, an evaluation of the system concludes the paper. The background and related work are provided as Supplementary Materials.

2. Forest early warning system

The proposed wildfire early warning system is based on the UAV, combined with BLE to implement automatic forest patrol and predict the possible eruption of wildfires.

2.1. System Introduction

The system is sketched in Figure 1. First, some OPs are selected in the surveilled forest, then the UAV takes off from the station and flies as scheduled along a fixed flight route, which covers all the OPs to collect environmental data and last the UAV returns back to the station. All the details about OP, UAV, BLEDC, BLEDA and station are described in the following sections.

Fig. 1. Visual depiction of the UAV system.

56 **2.1.1. Selection of OPs**

57 The OPs should be chosen in the middle of the surveilled forest, where that part of forest is impor-
58 tant or most vulnerable, then a BLEDC attached with a solar panel will be installed, which is a box
59 with sensors embedded in the surface. It will collect various sensor data continuously and dynamically,
60 then report to UAV as it arrives. GPS information of the OP will be recorded during installation.

61 **2.1.2. UAV Collecting Data**

62 A UAV equipped with a BLEDA will fly to the OPs according to the GPS information of OPs
63 in storage. BLEDA will connect to BLEDCs when they are inside the connected range, receiving
64 accumulated sensor data. When the UAV returns to station, BLEDA reports the data to a cloud database.
65 The Intelligent Flight Modes (DJI 2017) of the UAV are very helpful for the presented system and two
66 main features are employed. One is 'Waypoint', which are GPS points set in the memory of UAV to
67 guide UAV to fly to them automatically. In our system, those points are positions of the OPs. The
68 second feature is 'Point of Interest' (POI). If a point is set as a POI, the UAV will continuously circle
69 around it. Those two factors are employed to implement the process of this system; UAVs fly to the
70 first OP, circle around it and collect data, then the next OP until all OPs are visited.

71 **2.1.3. Station**

72 The station is the main base for UAVs, as it provides the resources that the system requires, includ-
73 ing the database server, Wi-Fi, recharging for UAV and BLEDA, etc. All the data is reported, reviewed
74 and analyzed here. Station and BLEDA maintain the same information table of all BLEDCs, every row
75 of table includes Bluetooth address, latitude and longitude. Latitude and longitude are basic GPS infor-
76 mation for a location of OP, they are recorded when the BLEDC is installed. The Bluetooth address is
77 a standard 48-bit MAC address which is unique and bound to a pair of latitude and longitude points in
78 the system, so as a result, if a BLEDC is replaced for any reason, this table must be updated to maintain
79 data validity.

80 **2.1.4. Communication by BLE**

81 BLE is designed to be a technology with lower power consumption and lower cost compared to
82 classic Bluetooth (Bluetooth SIG 2017), as it is widely used in computers and mobile phones. The
83 theoretical communication range of BLE is more than 100 meters, but reliable connection range relates
84 to actual scenario. In the presented system, reasonable distance is 20 meters considering the complexity
85 of the forest environment. Before Bluetooth 4.1, a BLE device is either master or slave, and cannot be
86 both. Only in this manner BLE is used in the system. The feature of low power consumption makes it
87 applicable for health, sport and smart home, etc. Before exchanging data between two BLE devices,
88 connection must be setup, which depends on advertisement. There are some different roles regarding
89 two devices in a BLE connection, for two BLE devices in the application, BLEDC and BLEDA, their
roles are shown in Table 1.

Table 1. Roles for equipment.

BLEDC	Advertiser/Broadcaster	Peripheral	Slave	GATT server
BLEDA	Scanner/Observer	Central	Master	GATT client

90 Most names are self-explanatory except GATT, Generic Attributes of BLE, which is a profile in-
91 cluding a hierarchical data structure to be exposed to connected BLE device, specifically, at least a
92 service and a characteristic, they are represented by Universally Unique Identifier (UUID). GATT
93 servers store environmental data and wait for a request from the GATT client. In summary, BLEDC
94 is the GATT server, peripheral and slave; it stores data from sensors, advertises and waits for request

96 from GATT client which is BLEDA in UAV. BLEDA is a master, central and scanner, when it observes
 97 the advertisement, it sends a request to the advertiser and waits for a response to connect, then receives
 98 data from BLEDC.

BLE works in the 2.4G spectrum which is one of the radio bands reserved for industrial, scientific and medical use, extending from 2402MHz to 2480MHz. The bands are divided into 40 channels, numbered from 0 to 39, each 1MHz wide and separated by 2 MHz. Advertisement happens in channels 37-39, they are not continuous in frequency on purpose to avoid blocking. The advertising timing is shown in Figure 2. Advertisement results in heavy power consumption as the radio is on, it is called the advertising event. For each event, BLEDCs advertise in all three channels one after the other, the maximum time duration in a channel is 10ms, scan and connect response happen in 10ms. The total time for an advertising event is expressed as $T_{AdvEvent}$ (Gupta 2016), given by Equation (1):

$$T_{advEvent} = advInterval + advDelay \quad (1)$$

99 Advertising interval ($advInterval$) ranges from 20ms to 10.24s, and advertising delay ($advDelay$)
 100 is a random value from 0-10ms. Fast advertising or slow advertising is decided by interval. Value of
 101 $advInterval$ decides consumption of power, small interval means fast advertising and connection, but
 102 more power consumed, on the contrary, big interval results in slow advertising and connection but
 103 saves power, so it is a trade-off between connection and battery life.

Fig. 2. Advertising timing chart.

104 When BLEDA wants to connect to BLEDC, it can initiate a connection by sending `CONN_REQ`
 105 in the same channel where it receives an advertising signal `ADV_IND`, or it can start from sending
 106 `SCAN_REQ` to BLEDC to ask for more information and wait for a response `SCAN_RSP`, then deciding
 107 to initiate a connection or not. The latter process will cost more energy of slave (advertiser) as it must
 108 be in RX mode to wait for `SCAN_REQ` then returns `SCAN_RSP` no matter there are any scanners or

not, this is applied between two stranger devices. In this system BLEDC and BLEDA are designed for each other, so BLEDA works in the first way, it just scans for advertising BLEDC, then sends CONN_REQ, and BLEDCs do not expect any SCAN_REQ, just CONN_REQ to save precious power. The timing is shown in Figure 3. There are similar parameters such as scan interval, scan window and scan duration for scan compared with advertisement to ensure connection is feasible and reliable. For the system, as BLEDA is rechargeable, power consumption is not the main concern so the parameters of scan are not discussed.

Fig. 3. Connection timing chart.

Two key components in the system are BLEDC and BLEDA, explained in the following sections.

2.2. BLEDC

BLEDC is responsible for collecting environmental data and reporting to UAV, whose structure is shown in Figure 4.

Fig. 4. BLEDC logical diagram.

Three main sensors, temperature, humidity and smoke detector are integrated to the IO of CSR1011, which is a single-mode BLE product from CSR. It collects data from those sensors dynamically, attaches a timestamp, saves to non-volatile memory (NVM) and reports to the BLEDA when it comes.

BLEDC plays the role of the GATT server in BLE architecture. According to BLE standard [18], as a GATT server, BLEDC must setup at least one Service with UUID and inside this Service there is at least one characteristic with UUID. BLE devices can be identified by this specific Service UUID. BLEDA uses this UUID to look for BLEDCs in the system.

Cyclical storage is designed for the application. A head pointer for reading and a tail pointer to writing are defined. For example, if 512 bytes are applied from NVM, both of pointers start from 1. When new environmental data arrives, tail increases to write; head increases when reading data. Head always chases tail; it reaches but not ahead. When the head reaches tail, no more data is available

for reading. When the tail or head reaches 512, next value will go to 1 again. This is the flexible and general way in practice.

Dynamic data means recording data based on threshold, which is a value between normal and abnormal. Data beyond thresholds will be recorded more frequently than normal. In this way, significant data is recorded and normal data can be ignored, as a result, it saves the power and memory of BLEDC.

CSR1011 is designed by consideration of power exhaustion, only a small 3v button battery (CS2032) can provide energy for months, but for the system, the solar panel is a better choice if it is feasible, in other words, if the OP receives enough sunlight for the panel, it is the first choice. No matter if the solar panel is used or not, energy saving is the first principle, as overcast could last long enough to exhaust solar power. In general, BLEDC only executes slow advertising based on the schedule, but in special situations, such as dramatic sensor value changes, it will keep slow advertising to the open possibility for connection from BLEDA to report event emergencies on-time.

Taking the wild climate and environment into consideration, the whole equipment adopts engineering plastics and sensors embedded on the surface to ensure exposure to the environment, and all materials should be chosen strictly to meet industry requirements.

2.3. BLEDA

It is carried by the UAV to approach OPs to receive data from BLEDCs. Its structure is shown in Figure 5. The core of BLEDA is ESP32, which is a Wi-Fi and Bluetooth combination chip; all the data collected from BLEDCs will be uploaded to the database on Station by Wi-Fi. A GPS chip is integrated to the equipment to provide accurate time and location information. Storage employs the similar circular management approach as BLEDC. Power supply in the BLEDA will be flexible as UAVs can return to the Station to recharge. LED applies different colors and flashes to represent various working situations. Long press of the button will power on or off the equipment and short press will change mode of BLEDA. There are two working modes designed for BLEDA, one is setup mode, the other is client mode.

Fig. 5. BLEDA logical diagram.

The purpose of setup mode is to confirm the GPS information of OPs. UAV carries BLEDA and flies on the patrol route to OPs, after all the GPS information of OPs are set to UAV as waypoints. Flying BLEDA starts BLE and scans for BLE devices which owns the Service with UUID of this system; if a BLEDC is connected, it reports the Bluetooth address of itself to BLEDA, then the current GPS information and Bluetooth address are saved into the NVM of BLEDA.

The client mode is the general mode of BLEDA. It is called client because BLEDC is defined as the GATT Server in Bluetooth 4.1 and BLEDA is the GATT client. Its main task is receiving data from BLEDCs. In flight, BLEDA keeps tracking the GPS information, compares it with GPS information of known BLEDCs which are stored in NVM; if it is similar or close to one, it opens BLE and starts scanning and connects to the BLEDC, and receives data and saves them to NVM.

2.4. System Setup Procedure

This procedure makes sure that the information of BLEDCs is consistent with the original selection of OPs whose information is recorded in the Station. The procedure is shown in Figure 6. The flow chart explains itself and the detail of BLE is hidden.

Fig. 6. Setup procedure flowchart.

UAV starts from the Station where all the recorded information of BLEDCs are set as Waypoints, and its working mode is the setup procedure. When in flight, it scans BLEDCs by Bluetooth. If any BLEDC responds, BLEDA records the Bluetooth address and current GPS information in NVM. If all the waypoints are explored, UAV returns to Station and reports collected information of BLEDCs.

On the BLEDC side, it performs slow advertising at the beginning, waiting for connected request from BLEDA, reports its own address to BLEDA, then starts scheduled slow advertising. Slow advertising is a way for BLEDC to notice BLEDA that it is waiting for connection; compared with its counterpart, fast advertising, it saves energy, as it is still a waste of energy if it keeps advertising.

This is a one-time effort if the collected information of BLEDCs are identical with contents in the Station. Application in the Station server will compare the information BLEDA collected with records of OPs; if any difference emerges, further investigation is needed. All human error and performance of UAVs should be ruled out first, then coverage range of BLE should be taken into consideration as it can be affected by environment remarkably.

The procedure will be repeated until all the information of BLEDCs are confirmed.

2.5. Routine Procedure

Routine procedure is repeated several times daily depending on the demand of the project, which is displayed in Figure 7. Compared to the setup procedure, the routine deserves more elaboration, time synchronization and scheduled slow advertising are normal steps; exception handle is only necessary if there is exception, but it makes the procedure complete.

Fig. 7. Routine procedure flowchart.

First of all, UAV is set as client mode and all the waypoints are set. When in flight, BLEDA checks current GPS information and compares it with the GPS information of waypoint; if they are close, BLEDA begins scanning and connects to BLEDC, it will download the current time to and receive data from BLEDC after connection, then flies to next waypoint.

For BLEDCs, in general, it performs scheduled slow advertising after setup procedure. If connected by BLEDA, it first receives time from the GPS and updates its own time, then uploads data stored in NVM, after that the status stays as scheduled slow advertising.

The above description is the normal flow of the routine procedure; time synchronization and scheduled slow advertising are explained below.

2.5.1. Time Synchronization

The system clock of CSR1011 is based on a crystal oscillator which drifts with time and temperature, so it causes issues with accuracy. Errors will be accumulated and become large as time passes, therefore it should be corrected with accurate time from GPS. A significant step of routine procedure is time synchronization, which happens right after BLEDA is connected to BLEDC; BLEDC receives time by the way of concerted protocol, and updates its own time which will be used from then on, and uploads sensor data to the BLEDA.

2.5.2. Scheduled Slow Advertising

In a routine procedure, scheduled slow advertising is employed instead of slow advertising which is employed in the setup procedure. The former is scheduled, so only slow advertising in a certain time with certain interval, and the latter always advertises in a slow way. The necessity of the former approach is power efficiency which is a key topic in WSN, as it is possible that cloudy and rainy weather could last long enough so that power from the solar panel is insufficient.

As waypoints are applied in UAV, the path and distance is relatively fixed, and the flying speed is stable, so it is affirmative that the total duration of one routine procedure is countable. For instance, if the UAV is scheduled to fly once an hour, the duration for a UAV to fly from the Station to the targeted forest is 5 minutes, and duration for the UAV to collect all the data from BLEDCs is 10 minutes; so BLEDCs are scheduled to start slow advertising once an hour at 5 minutes past the hour, and last 10 minutes, once connected, not advertising in the same hour. If the schedules fulfill the requirement of the procedure, it is satisfactory and saves energy. If BLEDC can only advertise when BLEDA arrives, it is the best situation. The accurate advertising time synchronization can be developed in concrete projects. A normal daily total advertising time T_{adv} is displayed in Equation (2):

$$T_{adv} = N * T_{flight} / T_{advEvent} * 30ms \quad (2)$$

N is daily scheduled flight frequency, T_{flight} is the total flight time before the UAV reaches the first OP and after it leaves the last OP, 30ms is the total maximum advertising time for 3 advertising channels of one advertising event, which is mentioned in 2.1.4. If the power consumed in each advertising event is known, the total power used in advertisement is calculable. This provides the possibility of prediction of life of battery.

As there is an interval between two consecutive flights of the UAV, if fire happens within the interval, it will be missed by the system according to the current procedure; but generally, fire develops gradually, so the exception handle mechanism can minimize the possibility of overlooking with a suitable interval.

2.5.3. Exception Handle

Station exists as a support center, as it provides a Wi-Fi router for the UAV to access to Internet, so all the collected data from BLEDCs of every routine procedure will be uploaded to the data server as soon as the UAV arrives back at its station. As each new data arrives, applications in server reviews the data first, they check the degree of deviation of various sensor data applying their thresholds as references. If any abnormal data occurs, depending on the degree of exception, frequency of flight is increased or an emergent flight is started immediately to catch all the possible issues of the surveilled forest. Likewise, BLEDC has the same mechanism to check sensor data; if emergence appears, it will start and keep slow advertising and waiting for connection from BLEDA to report data until the data returns to normal and its advertising mode goes back to scheduled slow advertising. In this way, the possible problem of the surveilled forest is not missed, so the effectiveness of the system is kept.

3. Results

There are two key factors for the success of the system. The first one is the communication between BLEDA and BLEDC, which is implemented by BLE. Connection is the main concern, as it is the source of monitoring data. The other factor is the accuracy of monitoring data from BLEDC. Experiments focus on these two factors.

BLEDA is under development, but it can be replaced by an ordinary mobile phone which is equipped with BLE and GPS. An iPhone 6 (Apple Corp.) was used in experiments, as it fulfils the hardware requirements. CSR provides the sample App to scan and connect peripherals based on the CSR chip and read data efficiently and smoothly. An iOS App was developed based on the implementation of CSR to achieve all the procedures of BLEDA.

CSR1011 is the core of the BLEDC, temperature sensor is TMP112, SHT20 is alternative option as it is a combination of temperature and humidity sensors. A CSR1011 is connected to two TMP112s and one SHT20, and powered by a CR2032 button cell battery. As the choice of smoke detector is still under consideration, the current prototype is used to check feasibility of the system.

In experiments, three BLEDCs were hung on trees for several days, with a minimum distance between each other of $>100\text{m}$, to avoid confusion of GPS data. Then their GPS information are set to DJI Phantom4 as waypoints, and each waypoint is set as a POI, so the Phantom4 can fly to those positions and circle around and receive data. Data of different points are saved in mobile storage as separate files, so they can be accessed and evaluated later.

3.1. Connection

There is no doubt that if BLEDC advertises faster and longer, it is easier for BLEDA to scan, connect and receive data, but this will result in exhausting the energy of BLEDC, which precludes power saving. So a balance between reliable connectivity and economical power consumption should be found for the system.

As introduced before, the AdvInterval parameter will decide how often BLEDC advertises in the scheduled slow advertising plan. The suggested range of AdvInterval is from 20ms to 10.24s according to Bluetooth Core Specifications (Bluetooth SIG 2017). Firstly, several seconds is not under consideration as UAV cannot wait for long to connect. Different AdvIntervals are tried, with Figure 8 showing the comparison of 1280ms and 2560ms in connection duration. For the scatter picture, the Y-axis is the connected time duration, unit is in microseconds, which is the X-axis of the histogram. The original data is from the iOS App which logs the timestamp of starting connection and connected message reception. The accuracy of data is related to the performance of the mobile phone and app, but comparison is valuable if they are collected from the same device. The result shows that for 1280ms, most of connected duration is under 3000ms, mean is 1500ms; for 2560ms, the maximum connected time is 5000ms and mean is 3000ms. Connection fails are not shown in the figure, based on statistics of the same data, about 20% connection attempts failed at 2560ms, instead the fail rate of 1280ms is under 5%. The conclusion is that AdvInterval = 2560ms is not acceptable, while 1280ms can provide reliable connection for the system.

3.2. Real-time data

To check the accuracy of sensor data, experiments lasted several days. Two typical sample data are displayed in Figure 9 and Figure 10. The data in Figure 9 is from about 20:00 of 09/21 to 18:00 of 09/22, almost a whole day of a typical summer. Temperature is expressed as Celsius and humidity as percentages. In about 7am, humidity reaches its highest and temperature at its lowest; in contrast, in midday, about 13:00, temperature in its highest, 55C, and humidity at its lowest. At other times, changes are accordant with natural law, temperature and humidity develop in variations alternatively.

Fig. 8. Choice of AdvInterval. (a) Scatter of connected time when AdvInterval = 2560ms; (b) Scatter of connected time when AdvInterval = 1280ms; (c) Histogram of connected time when AdvInterval = 2560ms; (d) Histogram of connected time when AdvInterval = 1280ms.

276 Figure 10 is the data of three days of rain in a row. From the afternoon of the first day, it starts
277 raining, humidity rises and temperature drops drastically. Humidity keeps in the high situation, even
278 in the midday, so the lowest percentage value of humidity is still higher than the highest Celsius value
279 of temperature. The results are highly accordant with actual weather, which confirms feasibility of the
280 system.

281 **4. Discussion**

282 UAVs act as forest patrol workers, as they can repeat the process without fatigue to collect sensor
283 data. Not only that, but also photos and videos from action cameras which are usually mounted in the
284 UAV, as the combinations will provide a better profile of the surveilled forest. The system is automatic
285 and economical with a one-time investment and long-term benefit, that can find hidden dangers of
286 wildfire in advance, if measures can be taken before the explosive outbreak of wildfires, so the system
287 is successful and beneficial to preserve the environment, as well as properties and human life.

288 Compared with other systems, such as ForestWatch (Envirovision 2015)/FireWatch (IQ-wireless
289 2017) and FFF (Almeida and Vieira 2017), the advantage of the presented UAV system is its low cost.
290 First, all three systems need a station or backend to store and analyze data, demands determine size/cost
291 of station, so cost of station is not calculated. For devices deployed outside in the presented system,
292 the cost of BLEDC is about 50 USD and BLEDA is under 100 USD. UAV equipped with Intelligent

Fig. 9. Results of normal summer day line chart. **Fig. 10.** Results of three rainy days line chart.

293 Flight Modes is less than 2000 USD, and the price keeps falling. As a result, for a small community, an
294 early wildfire warning system based on UAVs requires an investment of less than 5000 USD, although
295 some skillful pilots/technicians should operate the system and this adds to the cost. Other factors in
296 comparison of in-use fire detection systems are listed in Table 2.

Table 2. Comparison with fire detection systems in use.

	ForestWatch/FireWatch	FFF	UAV
Cost	high	moderate	low
Technique	optical camera	optical spectroscopy	sensor
Delay	minutes	minutes	minutes
Range	15-50km	15km	5km
Work	24h	day	24h
Automation	semi-auto	MHI	semi-auto

297 The choice of candidates for comparison deserves an explanation in detail. Firstly, ForestWatch
298 and FireWatch are combined as one candidate because the technique they employ is similar, FireWatch
299 claims their wider spectral camera can see more, in an ideal condition the range of detection is up to
300 50km. Systems based on satellites is not included in the comparison as current literature indicates a
301 detection delay within hours.

302 Delay of fire detection is a key parameter to judge the performance of systems, but no concrete
303 data is provided by the three candidates, because it is volatile and depends on the current weather at
304 the time. First, cameras usually rotate continually and scan 360, one scan takes 2-6 minutes [48], so
305 the scan time is not a fixed number as it is weather related. When sky is clear and wind is fair, rotation
306 is fast; otherwise it slows down, speed must be controlled to see well and avoid false alarms. If smoke
307 is missed or not decided, it should wait for the next round to be identified. Even if the camera is fixed,
308 there must be a gap between the smoke first emerging and forming a good shape to be identified. It
309 heavily depends on the weather no matter how good the camera and algorithms are. Considering the
310 confirmed time is in minutes, the time to analyze the image and time to communicate with the backend
311 is ignored as they are at the level of seconds.

For the presented UAV system, in the worst possible conditions, total maximum delay time can be
evaluated by Equation (3):

$$T_{delay} = T_{flight} + 3 * T_{road} + T_{break} \tag{3}$$

312 As mentioned before, T_{flight} is the total flight time in the targeted forest, T_{road} is time for the
313 UAV to fly from station to the targeted forest. T_{break} is the break time between two consecutive flights.
314 If right after the UAV leaves the forest and the fire starts, this is the worst-case scenario. According to
315 specifications from DJI, the maximum speed is 50kph for Phantom 4, so if the distance from the station
316 to the forest is 5km, and route in the forest is 5km, T_{break} is 10 minutes, so the possible maximum
317 delay is $(3*5km+5km)/50kph*60min/h+10min = 34$ minutes. This is the worst-case scenario, so ulti-
318 mately the total delay time depends on how far the forest is, how big the forest is, and how long the
319 break time is. For the first question, the station is suggested to be near the targeted forest; the second
320 question, multiple UAVs are the solution; for the last question, there is inherent mechanism in 2.5.3 to
321 handle the situation. In general, the UAV will fly more frequently in summer than in winter. Time to
322 receive data at every OP will be seconds according to analysis in 2.1.4 and 3.1, so it is ignored in the
323 calculation.

324 FFF applies scattered sunlight spectra to assess the atmosphere in daytime; during the night, the
325 system switches to night mode and relies solely on image processing techniques to detect fire. All other
326 systems can work 24 hours a day. Only FFF works autonomously with Minimal Human Intervention
327 (MHI), all other systems are under the condition of semi-automation, usually they need supported

people to work in a control center in the station. The presented UAV system can reach autonomous status soon when the maintenance platform of UAV is mature, then the UAV can recharge and shelter autonomously.

The system heavily depends on the UAV, which is vulnerable in severe weather, such as storms or windy conditions, but if the purpose of patrol is monitoring wildfire, it is not a big issue, as wildfire usually happens in sunny hot summers, not in rainy days. The other weakness of UAV is its limited duration of flight caused by battery life, for large surveilled forests, UAVs should be considered and the flight schedule should be planned on volume and recharge time of battery in the UAV.

In the future, all the hardware should be redesigned reasonably. First, smoke detector could be either photoelectric which detects smoke optically, or ionization, in which smoke is detected by physical process; no matter which one is selected, it should be integrated into the IO port of CSR1011. Using mobile phone as BLEDA is a temporary solution as it is much higher than the designed plan of BLEDA in cost. It is a better option to integrate with UAV, as all the UAV manufacturers are opening their API for developers, so the hardware and software of UAV could be adapted to implement the control and procedure of BLEDA with just adding some components, following instructions of the official onboard SDK. It will result in cost savings.

The goal of the system is the prediction of wildfires, which depends heavily on big data. If collaboration with local forest administration is achieved, more and more data will be accumulated, and the prediction pattern will be more accurate by data analysis and deep learning.

Supplemental Materials

Background and related work

A review (Alkhatib 2014) compared four main sensory approaches of forest fire detection, which are human based observation, satellite system, optical cameras and WSNs; in seven aspects including cost, efficiency and practicality, faulty alarms repetition, fire localizing accuracy, detection delay, small fire behavior information and other purposes, it summarized such that four ways have advantages and disadvantages respectively, but optical cameras and WSNs are preferred. All the last three modern ways have attracted the attention of researchers.

Daily Advanced Very High Resolution Radiometer (AVHRR) images from satellite-based remote sensing are employed in investigation of fires across the Canadian boreal forest zone by LI et al. (2000). They successfully computed and mapped the fire statistics of Canada from 1994 to 1998 by exploitation of multichannel information. The result came with an underestimation on the order of 35% compared to traditional ways, which is mainly caused by cloud cover or limited satellite images. Daily images from the satellite fire monitoring system are delivered within 24 hours of reception of AVHRR. Koji Nakau et al. (2006) applied MODIS (Moderate Resolution Imaging Spectroradiometer) images to detect fires by a two-dimensional histogram method which is implemented by a threshold lookup table of infrared band. They found that some small sized forest fires were not found by fire fighters but by MODIS. Qualification and delay of images is the inherent weakness of satellite systems. Di Biase and Laneve (2018) updated their algorithm of SFIDE (Satellite Fire DEtection) in geostationary sensor-based forest fire detection and monitoring system, by introducing the sun elevation angle and contextual analysis, proving that the false alarm rate is reduced and admitted that further steps are needed to reduce the approximation in the fire localization. Yang H. et al. (2009) employed satellites in a different way by combining geographical information system (GIS) with cellular automata (CA), to predict the spread of forest fire and shortest path to fire when considering factors including meteorological, terrain and fuel type, etc. A multi-temporal method for next-generation geostationary satellite data in fire detection is proposed by Hally et al. (2018), as they employed Broad Area Training (BAT) method to extract the expected diurnal cycle of a pixel from the temporally rich data of the Advanced Himawari Imager, then thresholds are applied to detect thermal anomalies. Results are 99% accordant with Low Earth Orbiting

(LEO) satellite, or 75% with the recorded fire. They believed detection time can be improved up to 6 hours with respect to LEO. Sahin and Ince (2009) take a step further by presenting a Radio-acoustic sounding system (RASS) to measure temperature changes of a forest by Radio-Acoustic Sounding, which consists of two main devices: radars with fire watchtower, which detects sound from the other device, and acoustic sources. The thermal map of forest is the visual result, reaching 80% accuracy of surface fires, but not for ground fires. Forest Fire Finder (FFF) (Almeida and Vieira 2017) is a device deployed outside for a forest fire detection system, based mainly upon differential optical absorption spectroscopy (DOAS), specifically, FFF measures and compares scattered sunlight spectra to detect higher-than-the-horizon smoke columns. The statistics of their practice showed that false events were high as they could be caused by air pollution factors.

For algorithms based on cameras, time of recognition along with confirmation of smoke and fire is the key measure of success. Habiboglu et al. (2011) proposed a real-time video-based smoke detection system that uses correlation descriptors with an SVM classifier. They employed temporally extended correlation matrices to combine color, spatial and temporal information together in the decision process. The algorithm has three stages: 1) slow moving object detection in video, 2) smoke-colored region detection, and 3) correlation based classification. As a result, time is related to the performance of the camera and computer. They proved that the proposed method is computationally efficient. ForestWatch (Envirovision 2015) and FireWatch (IQ-wireless 2017) are both commercial projects based on optical cameras and object recognition techniques. FireWatch claims that its multi-spectral sensors can cover a larger spectral range of 400-1100 nm instead of the visible spectrum between 400-680 nm. Forest-Watch has a small computerized image processing unit on site, which handles images before they are sent to the center. Both of them involve human operation and cost is their weakness.

One of the main application areas of WSN is surveillance, as it is employed in forest fire detection naturally. Hefeeda and Bagheri (2007) presented the design and evaluation of a WSN for early detection of forest fires. They focus on the Fire Weather Index (FWI) from the Canadian Forest Service, treat the forest fire detection problem as a k-coverage problem in WSN. In addition, they provide a simple data aggregation scheme to prolong the network lifetime by only delivering the data of interest to the application. The deployment in their simulation is not practical, as with increase of k, massive nodes are needed based on the algorithm, and nodes can fail quickly. A hierarchical WSN for early fire detection in risky areas was described by Molina et al. (2016). Advantages include: 1) no communication network in advance, 2) time from the GPS module, 3) not just fire early detection, but environment monitoring, 4) no cameras/images, and 5) middleware layer to share data. But time synchronization from CNs to SNs and relevant energy consumed are not elaborated in the paper.

Li et al. (2006) presented the system architecture, hardware and software framework of a WSN-based wildfire monitoring system. They claimed that the design can meet the goal of reactivity and reliability, robustness and network lifetime. Specifically, reactivity depends on threshold, reliability needs diagnostic phases and link quality-based routing protocol, robustness is achieved with water-and-fire-proof boxes, network lifetime is extended by a MAC protocol named SMAC and incorporating dynamic power management. The balance of coverage and cost is unaddressed, and location information of data is not solved. Zhang et al. (2008) and Ganesh et al. (2013) proposed similar systems based on ZigBee, which is a local area network (LAN) and runs on a mesh topology network. Son et al. (2006) implemented the system in South Korea, but emphasized on the function of software and network applications. Solobera et al. (2010) applied WSN with a special equipment named Wasp-motes, which integrates sensors affected by relative humidity, atmospheric pressure and temperature to detect fires. Lloret et al. (2009) focused on design, research and development of a wireless multi-sensor network which mixes sensors with IP cameras, with scalability of network and verification of fire as stress points. Zhu et al. (2012) proposed a system which collected data by WSN and reporting the data to a remote center by GPRS, but it depends on the fixed mobile communication network. Yu L. et al. (2005) presented a WSN system employing neural network whose input is measurement from

sensors and output is a weather index to the likelihood of fire. A complicated neural network requires strong computation and massive energy resources, which are a weakness of WSN (Zou et al. 2016). FIRESENSE (Kose et al. 2010) is a multi-sensor network to detect and manage fires to protect cultural heritage areas in the European Union, it performs fusion of data from WSN, optical and infrared cameras, along with the local weather index, by integration of techniques, such as pattern recognition and computer vision.

The popularity of civilian UAVs makes it a perfect tool for wildfire detection. A visual airborne forest fire detection patrol route planning system was presented by Peter Kourtz (1973). The scene is that a pilot flies an airplane in a planned route, and observes the forest on the ground for sign of wildfire. This is classified as human observation and the route is significant because of budget restrictions and time limitations if a wildfire occurs. The route is planned according to fire occurrence patterns from historical data. A report (Mathews et al. 2010) from Bushfire Cooperative Research Centre, Australia claimed the similar application of a dedicated spotter aircraft with human observer, and the majority of bushfire detection is from volunteer reporting of fire. Comparably, a current UAV is portable, flexible, intelligent and economical, and should be used effectively.

Tang and Shao (2015) reviewed applications of drones in forestry research and practice. They introduced some projects employing drones successfully, such as surveying, mapping, measuring, tracking of forest situation, and supporting intensive forest management, etc. and agreed that drones are very susceptible to weather and human-related accidents, and multidisciplinary collaborations to promote the standardization of drones are imminent. Paneque-Glvez et al. (2014) assessed the feasibility and future of UAVs in tropical area based on a project named community-based forest monitoring (CBFM). They found the advantages include high spatial and temporal resolution, generation of 3D drone image (Ota et al. 2017, Shahbazi et al. 2014) and monitoring of illegal activity and inaccessible areas are beneficial to participants, but disadvantages of small payload, weather sensitivity, short flight endurance and possibility of collisions limit its utility. UAVs are widely used in remote sensing applications (Ambrosia et al. 2011, Wing et al. 2013). Li et al. presented a localization framework of WSN (Li et al. 2011, 2012a,b, 2014) using dynamic path of mobile beacon (DPMB). Mobile beacon is an unmanned vehicle (UV) such as UAV or a driverless car, which is the master of the algorithm, it goes through processes of First triple, Flood 3, Try all 2 to locate sensors. Reinforcement Learning (RL) and Vector Cosine Similarity (VCS) are adapted to improve the efficiency of localization. The simulation proves that algorithms are lightweight and effective with help of UAVs. A bibliometric review of UAVs and forests are made by Gambella et al. (2016), which proves the prevalence of UAVs indirectly.

Wildfire detection applications spring up as UAVs become feasible to assist. Merino et al. (2012) proposed an Unmanned Aircraft System for wildfire monitoring, employing several aerial vehicles and a central station. Vehicles collaborate and automatically obtain wildfire information by means of on-board infrared or visual cameras, making decisions on the real-time progress of the fires front shape by applying techniques of prediction model, fire contours extraction, image vibrations eliminating and feature matching, etc. Their experiment showed that the system is applicable. At least two issues should be addressed, one is scale, their experiment employed 3 vehicles, but the coverage area is limited to the persons visual range. As many vehicles are used, collaboration is the other problem, such synchronization organization and paths to get useful vision is a key factor of their success. It will turn out to be very complex if more than one wildfire breaks out. Cooperation of UAVs is extensively discussed (Casbeer et al. 2005, Gancet et al. 2005, Lacroix et al. 2007, Maza et al. 2011a).

The architecture developed in the framework of the AWARE project in EU is a distributed and robotic platform, which integrates sensors from ground to aerial, to implement civil applications such as transportation, deployment and surveillance (Maza et al. 2011b). With WSNs on ground and UAVs in the air, cameras in between, they setup a 3D collaborative and comprehensive network. No doubt that more and more of the combined concept will be presented in the future.

472 **Additional Figures**

473 The normal typical scheduled slow advertising duration is shown in Figure S1 as a blue bar from
474 7am to 18pm.

Fig. S1. Normal scheduled slow advertising in BLEDC timing chart.

475 Figure S2 shows that at 10am and 15pm there are exceptions so scheduled slow advertising is
476 extended to slow advertising until the exceptions are handled.

Fig. S2. Extra slow advertising in BLEDC when exceptions timing chart.

477 The mobile is tied with the camera of UAV to work as BLEDA which is shown in Figure S3.

Fig. S3. Photograph of UAV with mobile phone.

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