A MULTI-SENSOR NETWORK FOR THE PROTECTION OF CULTURAL HERITAGE

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ABSTRACT

The paper presents a novel automatic early warning system to remotely monitor areas of archaeological and cultural interest from the risk of fire. Since these areas have been treasured and tended for very long periods of time, they are usually surrounded by old and valuable vegetation or situated close to forest regions, which exposes them to an increased risk of fire. The proposed system takes advantage of recent advances in multi-sensor surveillance technologies, using optical and infrared cameras, wireless sensor networks capable of monitoring different modalities (e.g. temperature and humidity) as well as local weather stations on the deployment site. The signals collected from these sensors are transmitted to a monitoring centre, which employs intelligent computer vision and pattern recognition algorithms as well as data fusion techniques to automatically analyze sensor information. The system is capable of generating automatic warning signals for local authorities whenever a dangerous situation arises, as well as estimating the propagation of the fire based on the fuel model of the area and other important parameters such as wind speed, slope, and aspect of the ground surface.

1. INTRODUCTION

The majority of cultural heritage and archaeological sites, especially in the Mediterranean region, are covered with vegetation, which increases the risk of fires. These fires may also break out and spread towards nearby forests and other wooded land, or conversely start in nearby forests and spread to archaeological sites. In addition to possible deliberate actions for harming a particular site, common causes of unintentional fires are human carelessness, exposure to extreme heat and aridity and lightning strikes.

For example, in the summer of 2007, Ancient Olympia, Greece, a UNESCO world heritage site and the birthplace of the ancient Olympic Games, was seriously endangered by a fast-moving wildfire. More recently in August 2009 in Greece, a multi-front wildfire raged the northeast of the greater Athens area and burnt 21,000 hectares of pine forest, olive groves, shrub land and farmland. Among the damaged areas was Marathon, site of one of history's most famous battlegrounds between the Greeks and the Persians in 490 B.C. and an area of supreme natural beauty. In July 2007, the 2nd century BC theatre and the necropolis of the antique city of Notion (Ahmetbeyli, Aegean coast, 50 km south of Izmir), Turkey, were partially destroyed by a wildfire. In February 2008, three houses in the Camiatik, Turkey, a district of Kusadasi near Ephesus, were burned. These houses were classified as 1st degree heritage sites. Other archaeological and cultural heritage sites that were threatened in Greece by wildfires in the last decades include: the ancient Kameiros, Rhodes Island in 2008, the temple of Epikouros Apollo in 1998, three Monasteries of Mount Athos in 1990 and a large fire at mountain Olympus that burned the scenic Scots-pine forest and the Dion antiquities in 1994 [1].

Beyond taking precautionary measures to avoid a forest fire, early warning and immediate response to a fire breakout are the only ways to avoid great losses and environmental and cultural heritage damages. Hence, the most important goals in fire surveillance are quick and reliable detection and localization of the fire. However, early detection of fire is traditionally based on human surveillance. This can either be done using direct human observation by observers located at monitoring spots (e.g. lookout tower located on highland) [2] or by distant human observation based on video surveillance systems. Relying solely on humans for the detection of forest fires is not the most efficient method. A more advanced approach is automatic surveillance and automatic early forest fire detection using either (i) Space borne (satellite) systems, (ii) Airborne or, (iii) Terrestrial-based systems.

Some advanced forest fire detection systems are based on satellite imagery, e.g. the Advanced Very High Resolution Radiometer [3], launched by the National Oceanic and Atmospheric Administration (NOAA) in 1998 and Moderate Resolution Imaging Spectroradiometer (MODIS) [4], put in orbit by NASA in 1999, etc. However, there can be a significant amount of delay in communications with satellites, because orbits of satellites are predefined and thus satellite coverage is not continuous. Furthermore, satellite images have relatively low resolution due to the high altitude of the satellite, while their geo-referencing is usually problematic due to the high speed of the satellites. In addition, the accuracy and reliability of satellite-based systems are largely affected by weather conditions. Clouds and precipitation absorb parts of the frequency spectrum and reduce spectral resolution of satellite images, which consequently degrades the detection accuracy.

Airborne systems refer to systems mounted on helicopters (elevation < 1 km) or airplanes (up to 2 to 10 km above sea level). They offer great flexibility, short response times and they are able to generate very high-resolution data (typically few cm). Also, geo-referencing is easier and much more accurate than the satellites. Drawbacks include the increased flight costs, flight limitations by air traffic control or bad weather conditions and limited coverage. Turbulences, vibrations and possible deviations of the airplane from a pre-planned trajectory due to weather conditions are additional problems. However, recently, a large number of early fire detection projects use Unmanned Aerial Vehicles (UAVs), which can alleviate some of the problems of the airborne systems e.g. they are cheaper and are allowed to fly in worse weather conditions, even if their utilization in most of European land needs substantial modification of actual European and national legislation.

Terrestrial systems are based on CCD video cameras, thermal or IR sensors. However, IR cameras are usually much more expensive compared to regular pan-tilt-zoom (PTZ) cameras, while the range of thermal sensors is limited. On the other hand, visible-range cameras can detect both smoke and fire, but it is almost impossible to view the flames of a wildfire from a camera mounted on a forest watch tower (unless the fire is very near to the tower), whereas smoke rising up in the forest due to a fire is usually visible from long distances.

As it is clear from the above, the majority of current wildfire surveillance systems do not realize the full potential offered by current technologies due to the lack of an integrated approach. To this end, in this paper we present a multi-sensor early warning system to remotely monitor areas of archaeological and cultural interest from the risk of fire. The proposed system will take advantage of recent advances in multi-sensor surveillance technologies, using a wireless sensor network capable of monitoring different modalities (e.g. temperature, humidity), optical and infrared cameras, as well as local weather stations on the deployment site. The work presented in this paper is part of the FIRESENSE (Fire Detection and Management through a Multi-Sensor Network for the Protection of Cultural Heritage Areas from the Risk of Fire and Extreme Weather Conditions) project, which is co-funded by European Union's 7th Framework Programme Environment (Including Climate Change).

2. SYSTEM OVERVIEW

The proposed system will be based on an integrated approach that uses innovative systems for early warning. Its main purpose will be to remotely monitor areas of archaeological and cultural interest from the risk of fire, while simultaneously providing weather data that can be used for efficient protection and preservation of cultural heritage assets. The system will take advantage of recent advances in multisensor surveillance technologies. The key idea is to place optical and infrared cameras as well as a Wireless Sensor Network (WSN) capable of monitoring the temperature on the deployment site. The signals collected from these sensors is transmitted to a monitoring centre, which employs intelligent computer vision and pattern recognition algorithms as well as data fusion techniques to automatically analyze sensor information. The system is capable of generating automatic warning signals for local authorities whenever a dangerous situation arises.

In a typical application scenario, multimodal wireless sensors are deployed at the site. The sensors acquire periodic measurements from the environment (e.g. ambient temperature, humidity) and provide their readings through the network to the monitoring centre. Optical cameras (visible and IR) monitor not only the site itself, but also the surrounding forested land. The collected measurements from multimodal sensors are fused in the monitoring centre for evidence or indications of fire in the monitored environment. In addition to periodic sensor measurements, events requiring attention can be triggered by activity, smoke or heat detection sensors. In case of fire detection, the system creates alert messages for the fire fighting management. Moreover, the system receives weather data from official weather information services as well as from local meteorological stations installed at the demonstration site and creates alerts in case of extreme weather conditions.

Detecting the starting position of a wildfire is only the first step in fire fighting. After detecting a wildfire, the main focus should be the estimation of the propagation direction and speed, in order to help the forest fire management. If the vegetation model and other important parameters like wind speed, slope, and aspect of the ground surface are available, the propagation of the fire can be estimated. Finally, a Geographic Information System (GIS) visualizes the predicted fire propagation in 3D, providing services for decision and operational support in forest fire suppression.

3. FLAME AND SMOKE DETECTION USING VISIBLE CAMERAS

In a computer vision based wildfire detection system, flame and smoke are the most important cues. At short distances flame detection is more feasible however for long distances it is impossible to detect flames therefore smoke detection is more efficient. In the FIRESENSE project we developed two algorithms, which detect flame at short distance and smoke at long distance, respectively.

A covariance matrix based flame detection algorithm [5] is used for flame detection. The video is divided into spatio-temporal blocks. From each block, color, spatial (color derivative) and temporal (flicker) information are extracted into a vector. Features are extracted from this vector using the covariance matrix method [6]. An SVM classifier is trained using the features extracted from the test videos. This SVM classifier is used for detecting the flame and non-flame blocks in a test video.

The covariance matrix based flame detection method [5] can work in real-time (at 20 fps, on a 320x240 pixel video). It achieved a substantial increase in the detection rates, compared to the state-of-the-art method [8]. Moreover, false alarm rates are also decreased. However, the flame detection methods are not effective in case of detecting wildfires at far distances. Actually smoke emerges first in wildfires therefore detecting smoke is more feasible.

An online Adaptive Decision Fusion (ADF) framework is developed for smoke detection [6]. In this framework, several sub-algorithms each of which yields its own decision as a real number centered on zero, are combined. The five main sub-algorithms used in the ADF framework are (i) slow moving object detection in video, (ii) smoke colored region detection, (iii) wavelet transform based region smoothness detection, (iv) shadow detection and elimination, and (v) covariance matrix based classification. The decision values of the sub-algorithms are linearly combined using weights, which are determined during the training procedure. This general framework is tested with standard datasets to combine the decision results of different classifiers. An example output of the ADF based smoke detection is shown at Figure 1. The experimental results given in [7] show that by ADF the learning time of the system is decreased. Moreover, it is also observed that error rate of ADF is the lowest in the test data set, compared with other schemes given in [7].

Figure 1: A snapshot from the test of the ADF based system.

4. FIRE DETECTION USING MULTISPECTRAL IMAGING

Two multisensor electro-optical imaging systems are designed specifically to detect automatically forest fire at the early stages by using multispectral emissions. Fire image recordings were realised at short ranges in a controlled environment in different spectrums. The visible waveband from 0.4 to 0.7 µm, the short wave infrared waveband from 0.9 to 1.7 µm, the middle wave infrared waveband from 3 to 5 µm and the long wave infrared waveband from 8 to 12 µm were selected for the experiment. The MWIR band detectors although they are optimal for fire detection are expensive due to the cooling engine. This is the reason why the visible and LWIR bands are mainly used. In the near future the uncooled SWIR will be a good candidate to locate fire.

A first order approximation end to end physical model is realised to estimate the detection range of the fire. The spectral emission of the background and the fire are based on Planck radiation formula. The waveband is fixed by the selection of the cameras and the filters and the emissivity of the fire gases due to smoke particles is calculated by using the Quintiere equation. The in band atmosphere transmission is a function of the fire range and is often approximated by the Beer Lambert law. The collected signal depends on the optical parameters and the type of detectors. The target signal (fire) is expressed differently, if we have an extended target or a subpixel target. The detection range is calculated in function of the signal-to-noise ratio. If the difference of temperature between the fire and the background is small, sensitivity is the main parameter. If the sensitivity is high enough, the fire detection range is determined by the size of the fire and the geometrical parameters of the electro-optical system (Focal length, f-number, Internal field of view, pixel size)

Two outdoor, early fire detection electro-optical imaging systems were designed for short and medium ranges. At early detection, the flames are often not visible. The automatic fire detection will be based on a change of heat radiation and on the smoke. The heat is detected by a thermal calibrated LWIR microbolometer (Figure 2) and the smoke is detected by a visible camera.

Each pixel heat response is compared to the coldest average portion of the image. If the response is higher than a defined value, an alarm is generated. The result of the smoke detector will be fused with the heat detector at the decision level.

If the flame is visible at short range, the fusion with the visible camera (flame and heat features) and LWIR camera (temperature feature) will be done at the segmentation level. A fusion at the pixel and the segmentation level requires an image co-registration. The detection of fire or smoke is initially based on dynamic background substraction followed by an automatic gamma correction and k-means clustering. The quality of the blobs is improved by iterative morphological filtering.

Fire detection is calculated by visual and LWIR silhouette coverage analysis. If an alarm is generated based on the pixel ratio of heat pixels and flames pixels added to smoke pixels, further analysis will be based on low cost computation feature analysis (orientation disorder or spatial flame color disorder).

Figure 2: A snapshot from tests with LWIR cameras.

5. WIRELESS SENSOR NETWORK

Besides using optical sensors and computer vision techniques to detect and track fires, wireless sensor networks (WSNs) can be utilized as well. A WSN is a collection of tiny sensor nodes networking together to monitor a region and using wireless links report the sensed data to one or more data collection centres (base stations or sinks) where they can be stored, processed and analysed. Such networks usually involve a large set of nodes with limited computational and communication capabilities. Their lifetime is limited by their battery capacity. However, by carrying the sensed data through multi-hopping, they collaboratively provide effective coverage of the monitored area. A WSN can sense a variety of phenomena including ambient temperature and relative humidity, which are helpful for fire detection systems. However, since the data collection centres may also be affected by the fire, reporting events in a reliable manner requires the simultaneous routing of the data/information packets to multiple sinks. Moreover, sensor nodes should be capable of organizing themselves into a self-configuring network. There are various short-range wireless radio technologies available that can be used for sensor nodes e.g. IEEE802.15.4/Zigbee wireless networking technology developed for low rate and short-range wireless applications including wireless sensor networks.

Our system will be monitoring the cultural heritage areas by collecting different modalities periodically and will be capable of adapting its data collection periods according to the increased fire danger, i.e. the higher the risk of fire gets, the more increased will be the sampling rate of the data. This scheme will provide more accurate and robust results in addition to estimation of fire propagation.

The system will be adaptable to both single-sink and multi-sink scenarios. If only one sink is present in the area, the collected data will be routed to the sink by means of Directional Geographical Routing [9], relaying the packets to the nodes with minimal distance to the sink. In presence of multiple sinks the routing path will be determined according to a simplified version of Multi-Sink Load Balanced Reliable Forwarding (MLBRF) [10] which is an extension to Load Balanced Reliable Forwarding (LBRF) [11]. MLBRF decides locally the most appropriate sink for data delivery by combining local dynamic congestion indicators in the neighborhood of a sensor such as the number of contenders and the buffer occupancy levels with the distances of candidate relays using a low-complexity fuzzy inference system

6. ESTIMATION OF FIRE PROPAGATION

After smoke is detected, the next step is the determination of the possible propagation of fire. Research on 3-D fire propagation estimation and visualization techniques has been conducted, with the aim to simulate the spread of a wildfire and visualize it on a 3D or 2D display. The spread calculations are done using a library called ‘fireLib’. fireLib was developed using BEHAVE (Andrews 1986) algorithm, by Collin D. Bevins, USDA Forest Service Rocky Mountain Research Station. According to BEHAVE, fire propagation depends on a number of parameters (e.g. ignition points, fuel model, humidity, wind, terrain data and other factors). These parameters are either measured or estimated and are used either directly or after modifications. However, these parameters for each cell are assumed to be constant with respect to time. When a cell is ignited, the calculation of the ignition times for its neighbouring cells is performed. The propagation of fire from one cell to another depends on the ignitability of the cell, which is done only once per cell. This calculation yields an ignition time instant as well as an estimated flame length. However as time passes and fire propagates further, some of the parameters in some cells may change (e.g. wind, moisture, fuel type). This issue is not taken into account in fireLib model. To cope with this problem, we take into account the dynamically changing parameter values within a recursive computation of the ignition times. Flame length is calculated once when the cell is ignited. To have a more realistic visualization we scale the flame length with a function that is decaying in time after some maximum. By this way the calculation of the fire propagation on dynamically changing landscape is achieved.

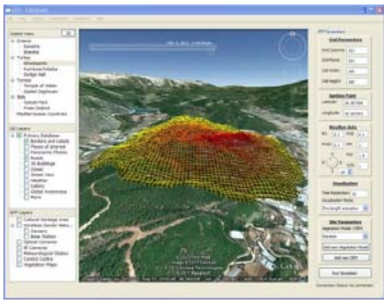

Figure 3: Estimation and visualization of the fire propagation.

Another problem is that the 13 fuel models defined by fireLib are not representative of the fuel models usually found in the Mediterranean region. To solve this problem new fuel models can be created through vegetation classification approaches based on satellite images and ground truth data. Commercial satellite images have reached a fairly high spatial resolution which allows more powerful textural analyses and more detailed description of soil surface. This improves the capacity to recognize and classify land uses, the amount and typology of vegetation and other potential sources of fuel for wildfires. It also reduces substantially the time and costs for updating vegetation and fuel distribution. Ground truth is also required especially for developing and testing of new image analysis algorithms. Measurements of the main fuel component are required and are usually destructive and costly, sometimes even unacceptable, especially if biodiversity or soil are threatened or in protected sites. Therefore, a sampling technique has been developed for single or groups of plants. Sub-volumes, which are characterized by the same type of fuel component and vegetation mix, are sampled over small known volumes. Volumetric mass densities are transformed into biomass and fuel components as mass per unit of surface.

Very-High-resolution satellite images (QuickBird) are ortho-rectified with a detailed DTM of the study area and analyzed: recognition of lines of water flux convergence, pathways, usually unrecorded on official maps, vegetation patchiness, connectivity lines for fire to spread more easily, and connectivity lines for water fluxes during rainstorms will be among the results.

Another approach that we use for vegetation classification is multi-band SVM classification approach. Each band characterizes/emphasizes a particular type of information such as textural, spatial, local and spectral information. The combination of these features improves significantly the accuracy of the results. We are currently investigating the registration between the ortho-rectified images and a ground truth map from the covered area in order to validate and improve the classification results.

The final phase is the visualization of the fire propagation. This visualisation is important since (i) it enables early intervention of the fire and (ii) it helps the fire department to deploy its forces wisely. The fire propagation software in the literature yield a 2D view (mostly a top view) of the fire-site, which may not provide a clear view of the situation to the persons responsible for the deployment of fire-fighting forces. In the FIRESENSE project, it is aimed to visualize this raw propagation data on a more user-friendly 3D-GIS environment. For this purpose Google Earth^{TM} is used in the system that has been developed (Figure 3). The main reasons of choosing Google Earth^{TM} are because it is public available and widely used by experts and non-experts. Also it allows the creation of impressive 3-D animations of the fire propagation, in addition to the static views. Some of the supported features are: a) Display of sensor locations and regions of interest in the cultural sites b) Interactive selection of some parameters (e.g. ignition point, humidity parameters) c) Automatic acquisition of weather data from onsite or nearby weather stations d) 2-D or 3-D visualization of fire propagation estimation output (ignition time and flame length).

7. CONTROL CENTRE

The control centre is used to remotely monitor the site and supervise the system state. It provides the user with an intuitive graphical interface (Figure 4) consisting of three screens to ensure more comfort to the user: the main screen, the video screen and the maintenance screen. The control centre supports numerous functionalities e.g. sensors configuration, view of data flow, alarms, statistics etc.

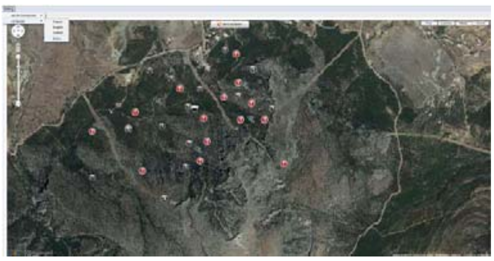

Figure 4: The main screen. The available sensors in the site are viewed as different icons according to their types (camera, temperature sensor etc).

8. CONCLUSIONS AND FUTURE WORK

In this paper, we presented a novel automatic early warning system to remotely monitor areas of archaeological and cultural interest from the risk of fire. The proposed system will take advantage of recent advances in multi-sensor surveillance technologies, using a wireless sensor network capable of monitoring different modalities (e.g. temperature, humidity), optical and infrared cameras, as well as local weather stations on the deployment site. Pilot deployments will be made in five cultural heritage sites in i) Thebes, Greece, ii) Rhodiapolis, Turkey, iii) Dodge Hall, Istanbul, Turkey, iv) Temple of Water, Tunisia, v) Monteferrato-Galceti Park, Prato, Italy.

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