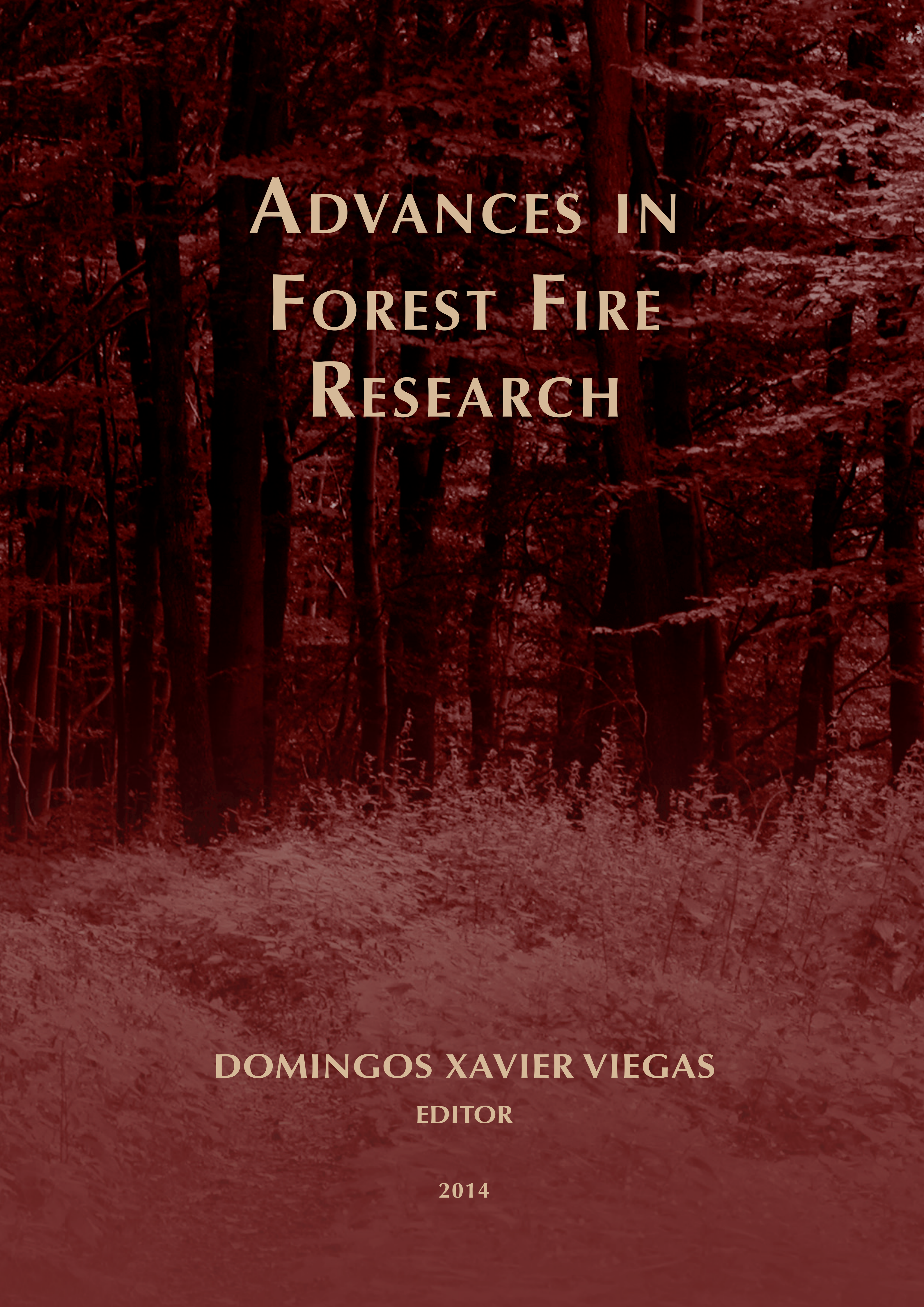

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Fire safety management based on integrated monitoring and forecast of smoke exposure

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Abstract
Decisions made by firefighters during suppression operations are highly dependent on personal judgement, experience, and senses. However, recent scientific and technological advances offer a vast number of possibilities towards advanced emergency preparedness during firefighting operations, if integrated in a single on-line platform. In this context, this paper addresses the following question: can models be successfully merged with personal sensors aiming to build an advanced Decision Support System (DSS) focused on the preservation of firefighter's safety, while pursuing an enhanced response to wildfires?
The goal of this research is to develop an emergency response support system for firefighting ground-based operations during forest fire events. The target of the under-development computational tool is to provide knowledge-based aid to firefighters at critical decision-making situations, helping with the safe and successful management of fire. This DSS will support the following features:
- capture of 'live' sensor data from a set of wearable monitoring equipment that will be based on a previously developed certified medical wearable technology named "VitalJacket®";
- capture of meteorological observations from a mast placed in one of the vehicles;
- enable projections of fire progression, smoke levels and critical exposure in a predefined time-step (up to 30 minutes);
- interpretation of results in an easy and intuitive form to be used by fire managers or firefighters involved in operations.
To achieve this goal hardware technology (e.g. wearable, mobile, communications) was combined with processing/simulation software algorithms that run under a user interactive interface. A data assimilation technique will allow near real-time observations from wearable monitoring equipment to be integrated into the exposure forecast modelling system, increasing the accuracy of the estimates.
A first prototype of the DSS, running in off-line mode, will be tested in the terrain during the fire season of 2014. An improved online version of the prototype will be tested in the following autumn in a series of prescribed burns.
In conclusion, this work proposes the development and testing (under real conditions) of a DSS intended to provide optimized firefighting efficiency, enhanced hazard awareness, and knowledge-based response to forest fire events. Advances in the computational modelling of fire and smoke behaviour, in conjunction with personal monitoring data, provide near real-time simulation of local fire conditions and short-term smoke exposure forecasts, with the needed advance in time to permit the safe and efficient positioning of crews in the terrain.

Keywords: *fire safety; smoke exposure; emergency response support system.*

1. Introduction

At the operational level, firefighters face extremely severe conditions including steep terrain, falling debris, obstructions to movement, heavy equipment, high temperatures, reduced visibility and toxic atmosphere. Smoke is, in this context, a magnifier of the destructive potential of fire. In fact, a significant number of the casualties occurring in forest fires is caused by smoke inhalation and consequent faint or disorientation due to heavily impaired visibility conditions [e.g., Miranda *et al*., 2005, 2012a]. Firefighters, in particular, are affected by short to long-term health disorders, as shown by several studies [Reinhardt and Ottmar, 2004; Reisen and Brown, 2009; De Vos *et al*., 2009; Reisen *et al*., 2011; Miranda *et al*., 2005, 2010, 2012a]. Miranda *et al*. [2010, 2012a] have shown that forest firefighting can expose firefighters to very high concentrations of carbon monoxide (CO), and also to high concentrations of nitrogen dioxide (NO_2), volatile organic compounds and particulate matter, with potential harmful effects on health, even in wildfires with small burnt areas. A particular concern is the peak and short-term exposure to CO because of the strong increase of the exhaled CO and carboxyhemoglobin (COHb) observed in firefighters after the exposure to smoke, meaning that the oxygen delivery to the body's organs and tissues is strongly diminished after smoke exposure.

Despite the advances on the numerical simulation of fire progression and smoke dispersion, operational models for assisting with decision are still limited in accuracy, resolution, and performance. Meteorological and air quality forecasts can provide some additional help but they are limited to coarse spatial and temporal resolutions.

However, recent developments on new sensor technologies, connectivity solutions and numerical models open unprecedented opportunities for anticipating or mitigating the risks associated to the inhalation of toxic gases. In this context, this paper addresses the following question: can models be successfully merged with personal sensors aiming to build an advanced Decision Support System (DSS) focused on the preservation of firefighter's safety, while pursuing an enhanced response to wildfires?

2. DSS development and testing

The goal of this research is to develop an emergency response support system for firefighting ground-based operations during forest fire events. The target of the under-development computational tool is to provide knowledge-based aid to firefighters at critical decision-making situations, helping with the safe and successful management of fire. This DSS will support the following features:

- capture of 'live' sensor data from a set of wearable monitoring equipment [Teles *et al*., 2011] that will be based on a previously developed certified medical wearable technology named "VitalJacket®" [Cunha *et al*., 2010; Cunha, 2012] [http://www.biodevices.pt];
- capture of meteorological observations from a mast placed in one of the vehicles;
- enable projections of fire progression, smoke levels and critical exposure in a predefined time-step (up to 30 minutes);
- interpretation of results in an easy and intuitive form to be used by fire managers or firefighters involved in operations.

To achieve this goal hardware technology (e.g. wearable, mobile, communications) was combined with processing/simulation software algorithms and user interactive interfaces. In that sense, and as a result of the requirement analysis, a conceptual architecture of the system was designed, as schematically represented in Figure 1, which relates the different modules and actors intervening in the process.

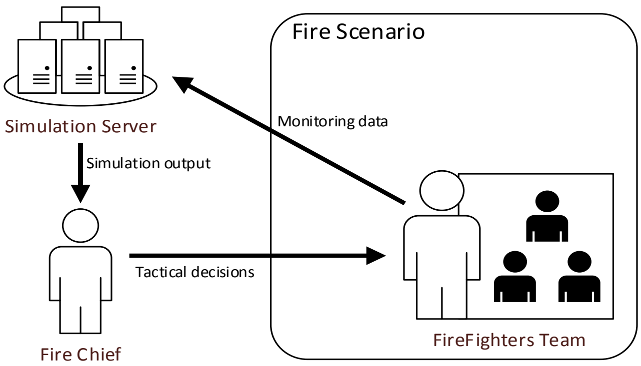

Figure 1. Schematic representation of system deployment.

2.1. General framework

As can be depicted in Figure 1 the dataflow relies on a modelling system capable of providing the needed information on fire and smoke behaviour. A simplified scheme of this integrated modelling tool is shown in Figure 2.

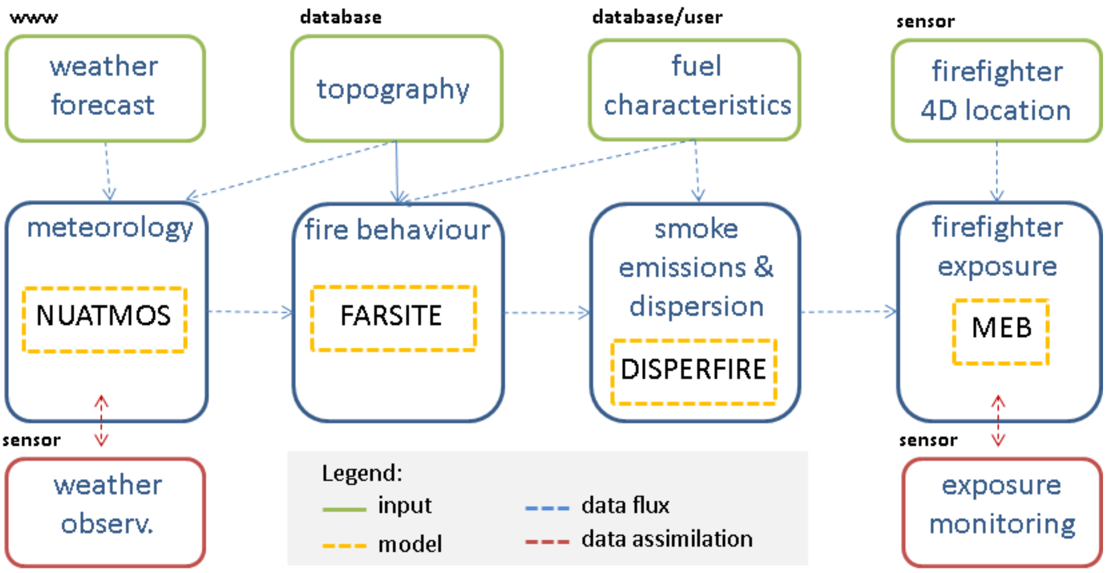

Figure 2. Schematic representation of the DSS core structure.

2.2. Graphical user interface

In order to provide a friendly way to interact with the end users, a JAVA Server Faces web interface called “VRTeam” was developed. This web developing platform was chosen because of its flexibility, for instance, the user can access the interface through any computing device (e.g., laptop, tablet, smartphone) with a standard browser and internet connection.

In terms of implementation, the interface works as a client application of two web services:

- "VRData", a JAVA Rest web service (jax-rs standard) that receives, processes and provides the monitoring data acquired in the terrain;
- "VRSimulationEngine", a JAVA WSDL web service designed to operationalize the numerical simulation models and return the results.

Concerning the interface graphical aspect, a hybrid approach between visual attraction and operability aspects was followed, as it is presented in Figure 3.

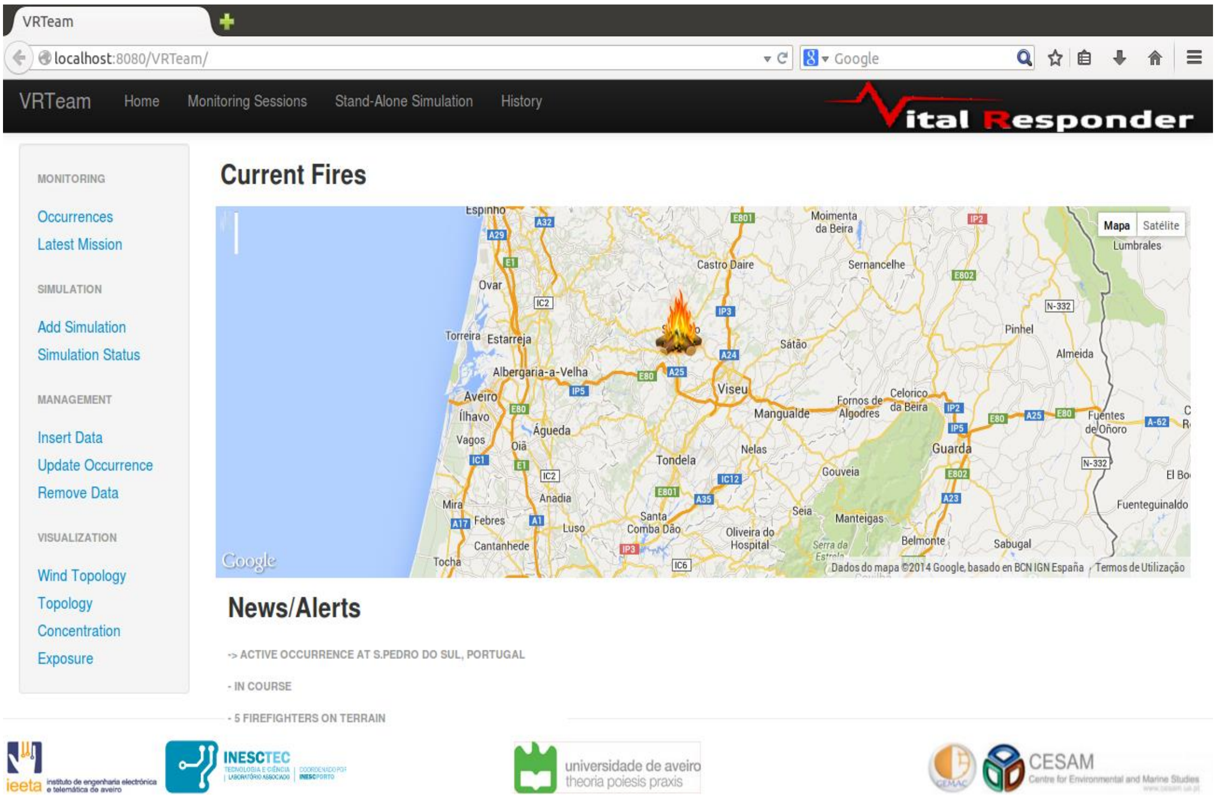

Figure 3. Main menu of the graphical user interface (GUI).

As can be seen in the above figure, the home page consists of a dashboard allowing users to view all active fire occurrences in course. Option buttons (in the left and top of the screen) are available that enable the access to all features provided by the system, namely:

- visualize monitoring data from active fire occurrences;
- simulate fire/smoke behaviour for an active occurrence;
- perform a stand-alone simulation for a random area.

Under development are other capabilities, such as the enriched visualization of occurrences history and monitored/simulated data, visual warnings of hazardous conditions for firefighters and advanced data analysis features for research purposes.

2.3. **Modelling system**

As shown in Figure 2 the numerical modelling architecture is composed of 4 independent models, which compose the main cores of the numerical system. These models are responsible for the simulation of local meteorological fields, fire progression, fuel consumption, smoke production and atmospheric dispersion, and human exposure. The numerical codes implemented have been previously tested [e.g. Valente *et al*., 2007] although not as an integrated system.

The different modules have been linked using a web service developed in JAVA (WSDL standard). This web application implements the workflow depicted in Figure 2 in a way that each numerical model corresponds to one execution stage. Any client application can make execution requests on the web service that are performed by the GUI application. Once an execution request is made, a simulation session for that user is created, and the forecast workflow begins. All related data is kept in cache so every user can have feedback about his simulation job status (see Figure 4).

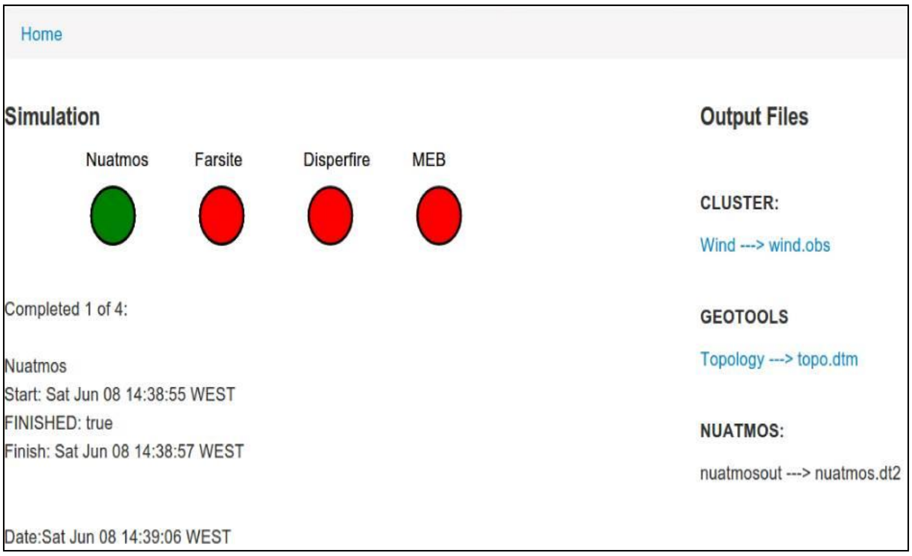

Figure 4. Example of GUI's feedback about the simulation status.

At the end of each execution, the results are stored in the cloud file system (e.g. Dropbox), and the outputs can be viewed using the GUI (section 2.5).
The main features of the numerical modules are hereafter briefly described.

Fuel

An adequate representation of the structural complexity and diversity of fuels, encompassing all the components that have the potential to burn (as trees, shrubs, grasses, woody material, litter, and duff) is needed for an accurate simulation of fire progression and smoke emission. Under development the incorporation into the system of a fuel classification tool based in the Fuel Characteristic Classification System (FCCS) [Ottmar *et al*., 2007] that will allow capturing the structural complexity, geographic diversity and potential flammability of typical Portuguese fuels. This tool is based in the concept of fuelbeds, which provides an easy identification of fuel characteristics in the terrain, and an accurate estimation of fire hazard and smoke emissions. Typical Portuguese fuelbeds were identified and built using the National Forest Inventory, other fuels datasets, published scientific literature, and fuel photo series. The mapping of the defined fuelbeds using vegetation classification and quantitative vegetation data is under development, as also the possibility of the user define the fuel model by selecting, through a touch-screen button, the corresponding image in the interface.

Meteorology

The diagnostic wind model NUATMOS [Ross *et al*., 1988], which has already been tested in this scope with good results [Valente *et al*., 2007; Borrego *et al*., 1999], produces a 3D mass consistent wind field through the interpolation of meteorological values distributed throughout the domain of interest. Instead of relying on meteorological observations, the system is connected to the meteorological forecast modelling system running at the University of Aveiro, thus providing also forecasts for the area.

Fire behaviour

The fire growth simulation model FARSITE [Finney, 2004] incorporates existing models of surface fire, crown fire, point-source fire acceleration, spotting, and fuel moisture. The model produces vector fire perimeters (polygons) at specified time intervals, which makes it adequate for the integration in the DSS.

Smoke behaviour

The estimation of forest fire emissions and the simulation of the atmospheric dispersion of the emitted pollutants are carried out by DISPERFIRE [Miranda *et al*., 1994; Valente *et al*., 2007]. Emission factors specific for southern European conditions, and particularly for the Portuguese forest and shrubland [Miranda, 2004], are implemented. The injection height of the smoke plume is estimated following the Sestak and Riebau [1988] methodology, while the subsequent transport and dispersion mechanisms are tracked using a 3D Lagrangian approach.

Firefighter's exposure to air pollution

It is important to distinguish between concentration and exposure. While the first is a physical characteristic of the environment at a given place and time, the latter quantifies the interaction between the polluted atmosphere and the person [Ott, 1982]. The exposure of each individual in the crew is estimated with MEB model [Miranda *et al*., 2012b], which follows the microenvironment approach from Hertel *et al*. [2001]. Basically, the time evolution of the exposure is simulated by tracking, in each time-step, the georeferenced firefighter's position and the corresponding concentration on that location and time.

2.4. **Data assimilation**

Under development is a data assimilation technique that will allow near real-time observations from wearable monitoring equipment to be integrated into the exposure forecast modelling system, increasing the accuracy of the estimates.

2.5. **Outputs**

As described, the system handles two types of data: monitoring data acquired by sensors on terrain and numerical forecasting outputs. Hereafter, the data provided by the system, and corresponding graphical output on VRTeam interface, are briefly described.

Monitored data

The system was designed to support a vast number of monitoring variables due to the scalability properties needed at this level (namely, the possibility of adding more sensors to the grid). At the present version the tool is capable of receiving, processing and displaying the following physiological and environmental variables:

Table 1- Monitored data.

Variable	Units
Terrain elevation	m
Atmospheric pressure	hPA
Air humidity	%
Air temperature	ºC
Luminosity	%
CO concentration	ppm
NO_2 concentration	ppm
Firefighter's location	UTM
Firefighter's heart rate	beats/min
Firefighter's R-R interval	s

The monitoring data is handled by *VRData* module. This module performs the caching of the last data received from the sensors in the terrain during half an hour periods (maximum caching time window). *VRTeam* interface consumes the online cache of *VRData* to present all information to end users, as line charts or custom grid tables (see Figure 5).

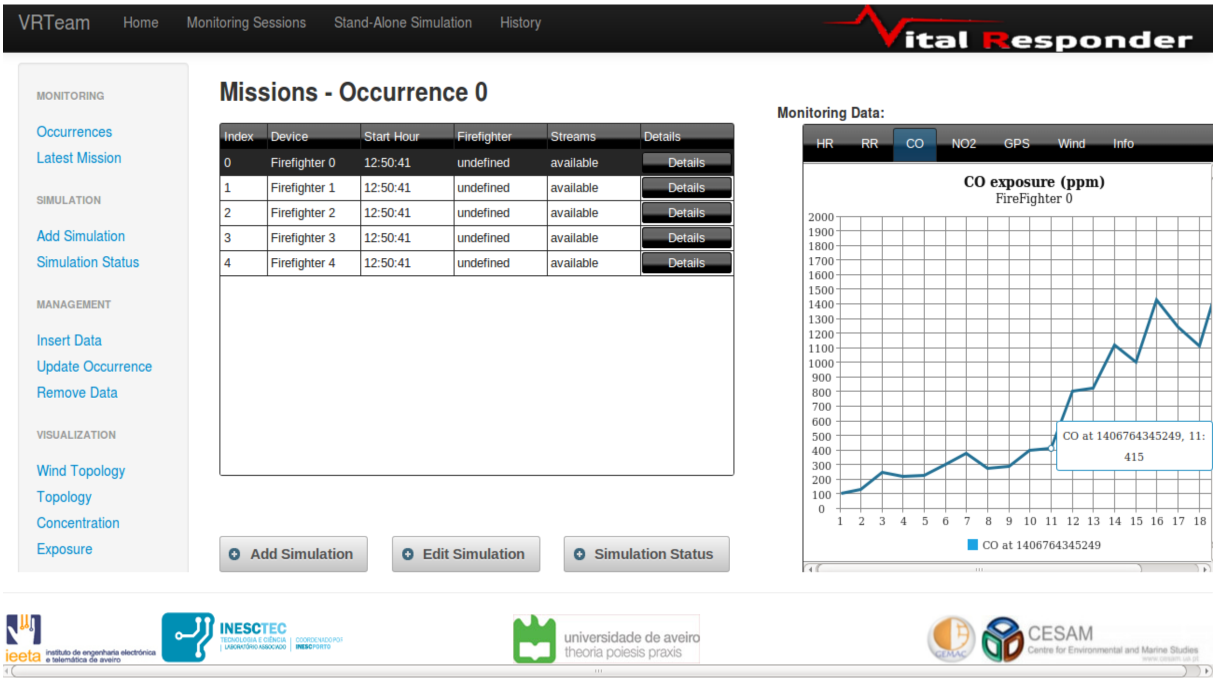

Figure 5. Example of monitored data shown in the GUI.

Simulated data

The results of the simulation's workflow are produced by the *VRSimulationEngine*, which runs the different numerical modules. Figure 6 shows an example of the information available to the *VRTeam* users after a complete simulation session. Enriched visualization of simulation results is shown using multi-dimensional representation of the outputs.

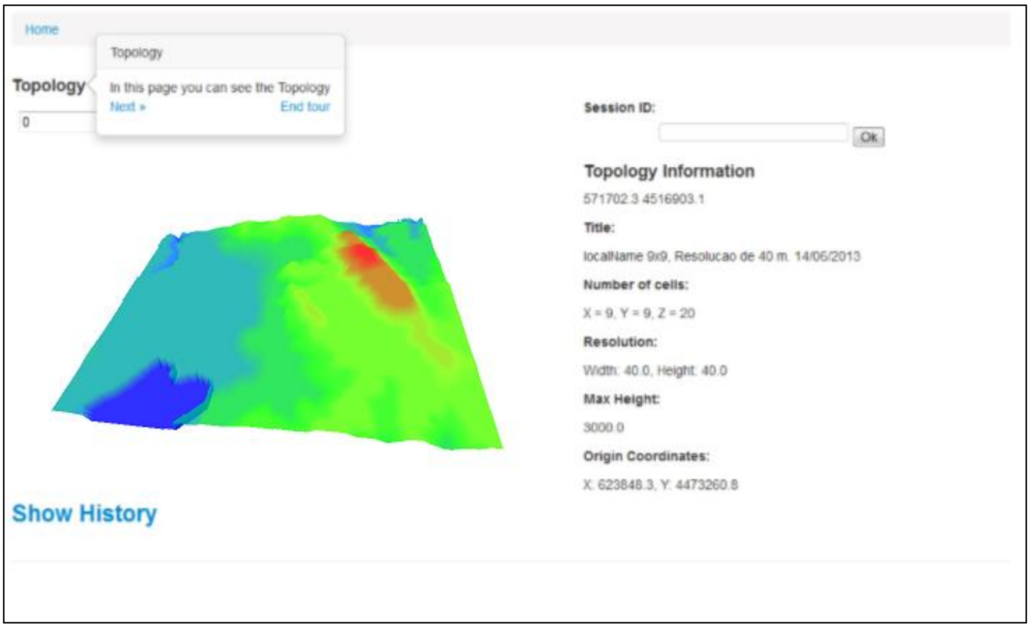

Figure 6. Example of simulation data shown in the GUI.

2.6. Operational testing

A first prototype of the DSS, running in off-line mode, will be tested in the terrain during the fire season of 2014. An improved version of the prototype will be tested in prescribed burning occurring in the autumn of 2014.

3. Conclusions

Decisions made by firefighters during suppression operations are highly dependent on personal judgement, experience, and senses. However, recent scientific and technological advances offer a vast number of possibilities towards advanced emergency preparedness during firefighting operations, if integrated in a single on-line platform.

This work proposes the development and testing (under real conditions) of a DSS that will provide optimized firefighting efficiency, enhanced hazard awareness, and knowledge-based response during wildland fire. Advances in the computational modelling of fire and smoke behaviour, in conjunction with personal monitoring data, will provide near real-time simulation of local fire conditions and short-term smoke exposure forecasts, with the needed advance in time to permit the safe and efficient positioning of crews in the terrain.

4. Acknowledgements

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