Ontology for a Georeferencing Mobile System for Real Time Detection and Monitoring of Wildfires

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Abstract: This paper presents the Georeferencing Mobile Wildfire Detection System Ontology (GeMoWilDSOn). This ontology served as a base for implementing software for a mobile and georeferencing system for real-time detection and monitoring of wildfires in steep mountainous territories. On average, about 65,000 fires occur in Europe annually, burning approximately half a million hectares of wild land and forest areas. This growing tragedy directly reduces the forest biomass and biodiversity, causing severe damage to the ecosystems. Ontologies help developers speed up the requirements' analysis in the design of a new system. Our work results in a streamlined ontology focused on fire prevention and fighting with mobile sensors, automatically georeferenced polygon data, and visible and thermal image captures, specially designed for steep mountainous terrain, where firefighting can be complex. Our research fills gaps found in related state-of-the-art and provides innovative contributions such as the concepts of manually drawn areas of fire and shadow, which are of utmost importance regarding this particularity of steep terrain. Our ontology was validated in three real-world tests where experts were delighted with the features, captured information, and its representation in the GUI of the developed system.

1 INTRODUCTION

This paper presents an ontology developed in the context of a research project financed by European Union funds. This ontology was a base for implementing mobile and real-time georeferencing software for forest fire prevention and fighting in steep mountainous territories.

Burnt areas in Europe have increased in the last couple of years, and up to mid-August 2022, more area has been burnt than in the years before (see Figure 1). On average, about 65,000 fires occur in Europe annually, burning approximately half a million hectares of wild land and forest areas (San-Miguel-Ayanz, 2012). This disaster also directly reduces the forest biomass and biodiversity, causing severe damage to the Earth's Forest ecosystem (Perez-Mato et al., 2016).

Being able to promptly detect the occurrence of a wildfire and having the capability to perform an accurate, real-time tracking of its evolution is vital to rapidly and efficiently organize the available resources to control and extinguish it (Arana-Pulido et al., 2018; Perez-Mato et al., 2016). This task can be severely compromised in areas of steep terrain, which not only makes the visual detection and surveillance of the wildfire fronts or hot spots difficult but also present localized winds and meteorological conditions that influence the prediction of wildfire evolution (Perez-Mato et al., 2016). The archipelagos of Macaronesia (Freitas et al., 2019) are steep, rocky, and with profoundly eroded lava gorges running

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down to the sea, which makes the fires' fronts challenging to spot and monitor.

Several key technologies and methods are commonly used for wildfire detection, surveillance, and prediction (Perez-Mato et al., 2016). These methods include fixed and mobile ground-based solutions, aerial platforms, and satellite imaging or sensing (Perez-Mato et al., 2016). However, most of them have specific limitations that might affect their performance and the usefulness of the generated information (Perez-Mato et al., 2016). Furthermore, algorithms used to predict wildfire spread relies on accurate near real-time input data to maximize their reliability (Perez-Mato et al., 2016). Unfortunately, most previously described technologies cannot provide data quickly or accurately enough (Perez-Mato et al., 2016).

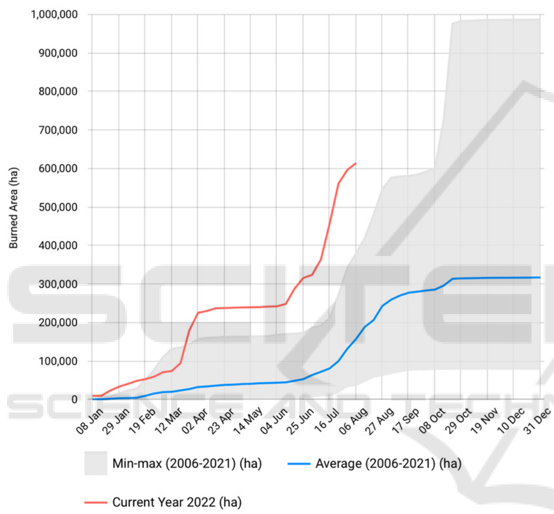

Figure 1: EFFIS Weekly Cumulative Burnt Areas in Europe, in 2022.

The georeferencing of the wildfire could also see some improvements. Most ground and airborne solutions only provide images of the fire, captured by thermographic or visual cameras, and leave the fire georeferencing task to the staff supervising those images (Perez-Mato et al., 2016). This adds a manual step to the process, which can be very slow and inaccurate in most cases, severely affecting the rapid decision-making scenarios required during a wildfire extinction process (Perez-Mato et al., 2016).

Perez-Mato and colleagues introduced a rapidly deployable mobile unit (RDMU) prototype. It uses a thermographic camera to autonomously detect, track, and georeference wildfires within its detection range (Perez-Mato et al., 2016). The data collected by these RDMUs is complex, needs to be safely kept, and be rapidly available for the firefighting staff members, both in real-time, to help in the fire extinguishing efforts, and *a posteriori,* to analyze the wildfire progression and behavior.

The list of requirements for the functionality of fire safety systems has been increasing in the last couple of years, while the time of implementation of software projects has been reduced (Nikulina et al., 2019). Ontologies may help developers speed up the requirements analysis in the design of a new system. Furthermore, ontologies may contribute to solving the problem of integrating knowledge from various sources and presenting it by subject area in an explicit form (Nikulina et al., 2019). In turn, it facilitates knowledge development, understanding, and maintenance, reducing duplications and inconsistencies (Nikulina et al., 2019).

This paper presents the ontology designed to formalize information supplied by a set of RDMUs, as well as decisions and commands issued by the intervenients. All information and commands are made available according to the needs of staff in an intuitive GUI.

The following sections present: the context of our work; a review of related work regarding ontologies for fires and sensors-based systems; our ontology proposal, which addresses the concrete needs of our practical project and its validation; a comparison between our approach and related work; and conclusions and future work.

2 SENSOR-BASED WILDFIRES DETECTION SYSTEMS

This section overviews the most widely used sensor-based wildfire detection systems. Most of these systems may also serve as: (1) tracking tools once the fire has started; or (2), in a post-fire moment, for firefighting staff and investigators to go back in the data and analyze the fire progression. The main features and limitations of these systems are presented.

2.1 Ground Detection Systems

Fire detection systems based on the ground are usually composed of cameras attached to watchtowers or similar infrastructures, which can provide the necessary power and communication interfaces (Perez-Mato et al., 2016). To be able to surveil large extensions of a forest, several of these observation points need to be installed, ideally accounting for the field of view (FOV) of each camera and considering the individual pan and tilt ranges, as well as the presence of any surrounding obstacles (Perez-Mato et al., 2016).

According to the literature (Perez-Mato et al., 2016), ground-based wildfire detection systems present the following main limitations: (1) cameras are permanently exposed to weather conditions and are prone to vandalism, which demands regular and pricey maintenance to keep the cameras operational; (2) the limited FOV demands numerous observation points to cover a large area; (3) the georeferencing of the detected fire is usually performed manually by firefighting staff, which is prone to error.

An alternative to ground-based wildfire detection systems is vehicles with thermographic cameras installed. This configuration increases the mobility and reconfigurability of the observation points and reduces the possibility of damage caused by weather and vandalism (Perez-Mato et al., 2016). However, they still suffer from the same subjectivity regarding wildfire georeferencing and pose a high risk for vehicle operators (Perez-Mato et al., 2016).

2.2 Aerial Detection Systems

Human-crewed helicopters and aircraft are often used during wildfires for firefighting and monitoring tasks, as they can spray water over the fire and serve as high-altitude observation points (Perez-Mato et al., 2016). Aircraft flying over a wildfire area provides a much larger FOV and can be dynamically moved from one place to another as the wildfire evolves. This makes them much more versatile and efficient than ground-based solutions (Perez-Mato et al., 2016).

The main limitation posed by these systems is the danger to the aircraft crew due to the proximity to the active fire and local turbulence, which may affect the aircraft's stability (Perez-Mato et al., 2016). This has been a direct consequence of many fatal accidents in the past.

Uncrewed Aerial Vehicles (UAVs) are now widely used for monitoring tasks under risky situations (Perez-Mato et al., 2016). However, there is concern about addressing a loss of control if they share the same airspace with crewed aircraft (Perez-Mato et al., 2016). Other typical limitations of commercially available UAVs are their limited autonomy, low payload capacity, and limited ability to withstand strong winds or turbulence (Perez-Mato et al., 2016).

Wildfire tracking using satellite imagery and multispectral sensing has often been employed when large extensions of land or forest are affected by a severe fire (Perez-Mato et al., 2016). The primary limitations associated with satellite-based remote sensing are the time it takes for the image to be available to the firefighters' staff and the low periodicity of images captured (Perez-Mato et al., 2016).

3 RELATED WORK

This section presents the most relevant ontologies within the scope of our project.

3.1 Ontologies of Fire Prevention Systems

The literature presents a few ontologies in the field of fire prevention and safety. A review of this field was compiled by Nikulina and colleagues (Nikulina et al., 2019). Some ontologies (Chandra et al., 2022; García-Castro & Corcho, 2008; Souza, 2014) are concerned with wildfires, while others focus on fires in buildings (Bitencourt et al., 2018; Fitkau & Hartmann, 2021; Nunavath et al., 2016; Tay et al., 2016).

3.1.1 Wildfires

An ontology of a Semantic Sensor Network for Forest Fire Management was presented in a study to semantically enhance fire detection alert inference methods by integrating meteorological information and deep knowledge mining from observational data (Chandra et al., 2022). The authors (Chandra et al., 2022) discovered that the system's running time rises while processing large ontologies owing to the enormous amount of information, which indicates that the framework's scalability must be improved. Researchers (Chandra et al., 2022) have considered adopting similar processing techniques, allowing several processors to examine various portions of the ontologies concurrently, improving the execution time.

The Fire Ontology Network (García-Castro & Corcho, 2008) and the Fire Ontology (Souza, 2014) are intended to fight forest fires and address the use case of wildland fire risk management. However, some parts of these ontologies may be used for other purposes, such as fires in buildings.

The Fire Ontology (Souza, 2014) represents the set of concepts about the fire occurring in natural vegetation, its characteristics, causes, and effects, focusing on the Cerrado vegetation domain. There are 53 classes and 19 properties in this ontology. It focuses on fire characteristics like area burned, fire frequency, fire intensity, fire severity, flame height, speed, and spread.

The Fire Ontology Network (García-Castro & Corcho, 2008) supports the project use case on forest fire risk management. This approach mainly reuses SWEET ontology (ESIP Semantic Team, 2022), which covers the following domains: fire, forest and vegetation, weather, geography, water body, infrastructure, location, and time. A SpatialObject class was added to represent objects that have a location, classes were identified to be considered as spatial objects (bodies of water, landforms, infrastructures, and fire), and the definition of datasets (to make them cover a region and a temporal extent) was extended (ESIP Semantic Team, 2022).

3.1.2 Fires in Buildings

The approaches Emergency Fire Ontology (Bitencourt et al., 2018), Building Fire Emergency Response (BFER) (Nunavath et al., 2016), and Building Ontology (Tay et al., 2016) propose ontologies for emergency fire situations, especially in buildings. They describe the emergency protocols aiming to enable end-users to respond quickly to fire emergencies in facilities. However, they do not focus on preventive fire safety.

The Preventive Fire Safety Ontology (PrevFis) contains general descriptions which present the topology of a building, as well as part of preventive fire safety, which is crucial for structural fire safety (Fitkau & Hartmann, 2021). Fitkau and Hartmann (2021) describe a general ontology based on a detailed rule-based data source, using the ontology development METHONTOLOGY (Fernández-López et al., 1997). This work (Fitkau & Hartmann, 2021) reports on real-world use cases successfully presented and concluded in PrevFis, collected in close cooperation with fire safety specialists.

3.2 Ontology of Sensor-based Systems

The Semantic Sensor Network (SSN) is an ontology developed by a W3C group for describing sensors and their observations, the involved procedures, the studied features of interest, the samples used to do so, the observed properties, and actuators (Haller et al., 2017). SSN follows a horizontal and vertical modularization architecture by including a lightweight but self-contained core ontology for its elementary classes and properties, called SOSA (Sensor, Observation, Sample, and Actuator) (Haller et al., 2017). With their different scope and different degrees of axiomatization, SSN and SOSA can support a wide range of applications and use cases, including satellite imagery, large-scale scientific monitoring, industrial and household infrastructures, social sensing, citizen science, observation-driven ontology engineering, and the Web of Things (Haller et al., 2017).

4 PROPOSED ONTOLOGY

4.1 Research Approach

Our proposed ontology of a georeferencing mobile wildfire detection and monitoring system was designed with the help of experts in the field of wildfire detection, prevention, and fighting, who were involved in the evaluation of each iteration. The initial core of our ontology was based on previous work on wildfire ontologies (Chandra et al., 2022; García-Castro & Corcho, 2008; Souza, 2014) and the SSN ontology (Haller et al., 2017). Thus, the alignment of the asserted knowledge was an incremental process built over several iterations.

The development of this ontology was based on METHONTOLOGY, a well-known methodology used to build ontologies from scratch (Fernández-López et al., 1997). It identifies a set of activities during the ontology development process: planify, specify, acquire knowledge, conceptualize, formalize, integrate, implement, evaluate, document, and maintain. METHONTOLOGY proposes the following steps: specification, conceptualization, formalization, integration, implementation, and maintenance (Fernández-López et al., 1997).

In communication with the domain experts, an initial conceptual model was developed , using the traditional Entity Relationship notation (Chen, 1976) and methods of DEMO and Enterprise Engineering, namely the Organizational Essence Revealing (OER) method (Dietz & Mulder, 2020). The knowledge represented in the initial conceptualization was then formalized in a more detailed way in an ontology represented in the Concepts and Relationships Diagram (CDR) (Gouveia et al., 2021; Pacheco et al., 2022), an adaptation of the diagram of the Generic Ontology Specification Language presented in Dietz and Mulder (2020).

The CDR is a generic, global, and synthetic view of an entire domain's concepts while abstracting from their attributes (Pacheco et al., 2022). In the CDR, a concept is represented by a collapsible box whose expansion discloses its attributes, one per line. The value type of an attribute is specified to the left of the line, while to the right is the attribute's name. The value type can be any of the following options: category, reference, document, text, doc & text, number, date, or boolean. Arrows express relationships, which will always consist of an attribute in one concept whose instances will reference instances of the other concept. Cardinalities are represented with arrows pointing to relationships' "one side". A dark-filled circle attached to a concept in one connector means that an instance of this concept, in order to exist, depends on an instance of the concept at the other end of the connector (Gouveia et al., 2021). The specialization/ generalization relationship is depicted using a connector with a pointed line (Gouveia et al., 2021; Pacheco et al., 2022).

In Figure 2, we can find our ontology's concepts, relationships, and attributes, together with their value types, essential for implementing software systems.

4.2 Ontology Description

Our proposal constitutes a Georeferencing Mobile Wildfire Detection System Ontology (GeMoWilDSOn). This ontology covers a mobile system's classes, concepts, and attributes to detect, monitor, and prevent wildfires. The GeMoWilDSOn includes information on the sensors, their configurations, deployments, geographic regions, campaigns, notifications, logs of executed commands, locations, and captures (georeferenced polygons, drawn polygons, and images).

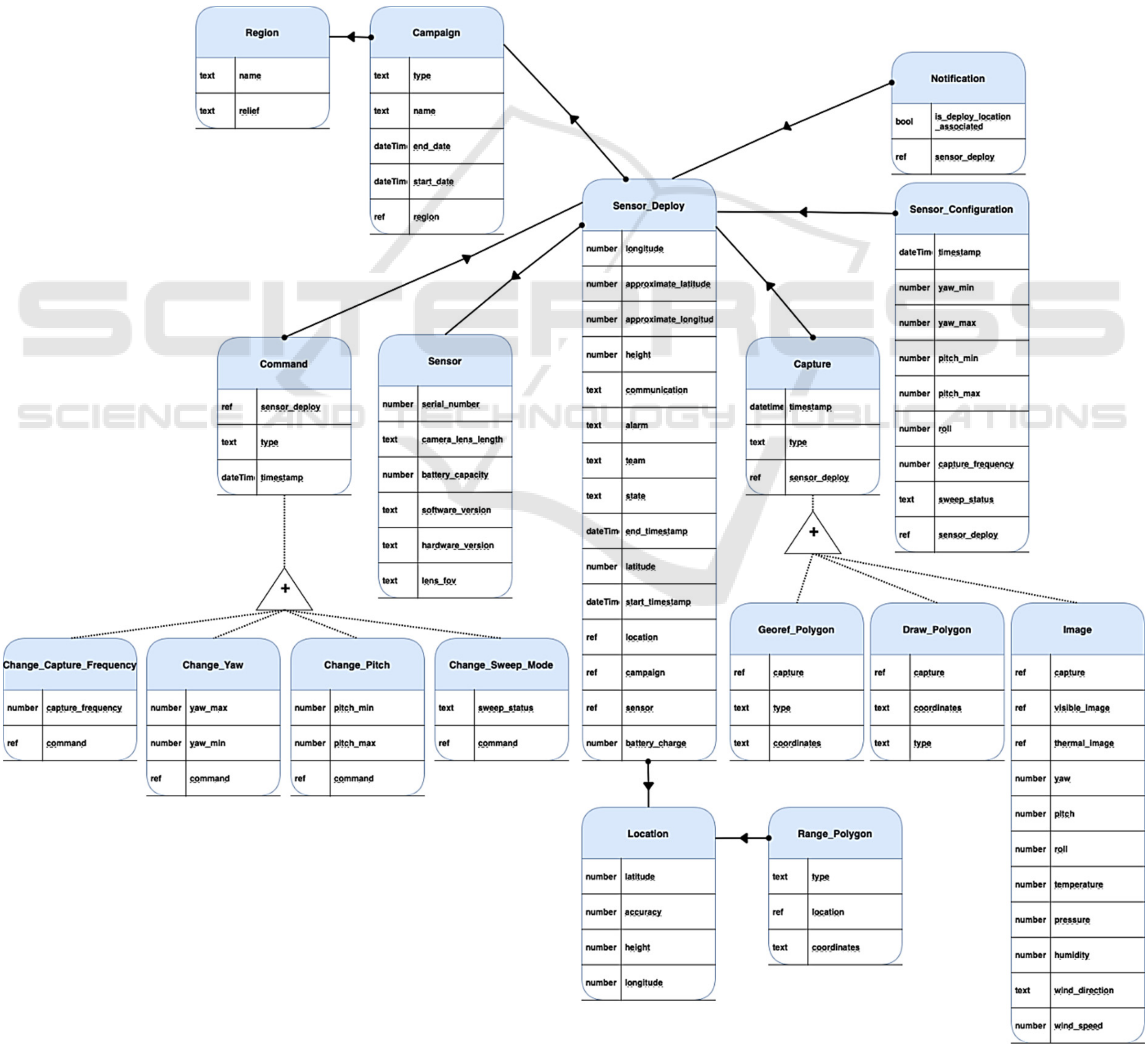

Figure 2: Concepts and Relationships Diagram.

The concept Region refers to a specific geographic area where the Wildfire Detection System will be used, the relevant attributes are the name of said region and the relief, that is, the type of terrain in said region.

A Campaign is an organized fire prevention activity in a set period (with a start and end date), that applies to a specific Region.

The Wildfire Detection System has as one of its primary tools Sensors (which include the ability to get visible and thermal images of the terrain). Each of these Sensors has a set of intrinsic properties of the equipment, namely serial number, a software and hardware version, a specific camera lens length specification, the expected field of view of the lens, and the battery capacity.

The concept of Sensor Deploy regards the use of the before-mentioned Sensors in specific Campaigns, deployed in a given Location within the region. These deployments take place within a specific timeframe (that can be the same as the Campaign itself) and therefore need a start and end timestamp. Other relevant attributes include: the latitude and longitude where it has been deployed (as well as a less exact approximation of said latitude and longitude); the specific height of the deployment; the type of the communication (for example, medium band); the alarm identification code; the team responsible for the deployment of that sensor; the current battery levels; and the state of the deployment (if it is ongoing, has ended or has any issues).

Each Sensor Deploy also needs a Sensor Configuration where the parameterization for that specific Sensor is set, although, during the deployment time, this configuration may be changed multiple times. The Sensor Configuration includes a timestamp of when it took place, a yaw and pitch range, a set roll (movement and position of the sensor within its axis), a capture frequency for the polygons and images, and the sweep status (if it is in sweep or fixed mode).

Despite the default Sensor Configuration, it is also possible to send specific Commands to take effect in the Sensor Deployment. These Commands can be of four different types; 1) Change the Capture Frequency, where the time between captures can be altered; 2) Change Yaw, where the range of the Yaw rotation can be modified; 3) Change Pitch, where the range of rotation of the Pitch can be changed; and 4) Change Sweep Mode where the type of Sweep mode can be changed.

When a Sensor Deploy is in use and depending on the set Capture Frequency, the Sensor will make multiple image captures. These Images contain multiple attributes, namely, the visible image, the thermal image, the yaw, pitch, and roll of when it took place, the temperate, pressure, and humidity of the area, as well as wind direction and speed. These captures are processed by georeferencing algorithms that take information from the thermal image, position of the sensor, and terrain information, namely contour lines, to produce polygons that represent areas that are for sure covered by fire and shadow areas that, due to the steepness of the mountains, one cannot be sure that fire is there or not. In the georef polygon concept, the attribute type indicates if the area is of type fire or shadow.

Operators may complement the capture with manually drawn polygons, both of fire and shadow types. Experienced fire prevention and fight coordinators will know, considering fire progression, local meteorological conditions, knowledge of the terrain, and other direct observations (by aircraft pilots, for example), how to complement the automatically identified fire and shadow areas. Such complementary information is essential for a more informed evolution of the fire and necessary decisions on how to allocate firefighting resources and possible changes of the sensors' positions. These modifications, might allow a complete view of the situation and more effective automatic generation of fire and shadow areas by the algorithms.

The concept of Location, before mentioned in the Sennsor Deploy, also has its own set of attributes with the latitude, longitude, height, and accuracy that are optimal for sensor deployment in said location. This optimal location may or may not be used in a specific deployment due to logistic reasons.

Each Location can also have a Range Polygon associated, which is a polygon that delimits the total visible area that the sensor can capture, considering the surrounding topography, like mountains that could block the view. This information is mainly used to pick the best location for deploying each sensor, maximizing the covered area.

The final concept is the Notification, which reports the association of a Sensor Deployment and a specific predetermined Location (or not).

4.3 Validation

The ontology was validated in real-world tests that took place in three archipelagos in Macaronesia: Cabo Verde, Madeira, and Canaries. These tests relied on the involvement and contribution of teams of experts from different local wildfire prevention and fighting services, in particular, Instituto das Florestas e Conservação da Natureza (Madeira), Cabildo de

Gran Canaria (Canaries), and Serviço Nacional de Proteção Civil e Bombeiros (Cabo Verde).

A complete hardware and software system was developed, allowing real-world tests and ontology validation. Figure 3 shows a diagram of the system's architecture.

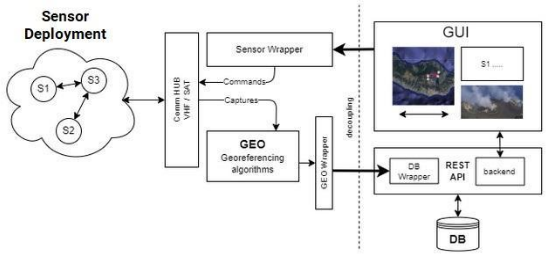

Figure 3: Architecture of the system.

The system's hardware is constituted by a set of mobile sensors (cameras that capture both visual and thermal images) and two web servers. One of the servers, implemented by our project partner, handles sensor information processing and command reception. The other server, developed by us, aggregates the database, sensor information reception interface as well as a GUI component.

The GUI is composed of three visors. The MainVisor shows a satellite or contour line view of the terrain, as well as real sensor positions (camera symbols), their range of observation, and fire and shadow polygons, both the automatically generated and the drawn ones. In a layer selection feature, one can choose to see all types of polygons or just a few. This visor also has a timeline feature where one can navigate through a set time interval, to view, analyze, and eventually draw/edit/delete the polygons. The NodeVisor displays more detailed information about the selected sensor and also allows the user/operator to send commands to change some of its settings. The ImageVisor shows the images, both visible and thermal, that were captured by the selected sensor in the time and date that is currently selected in the timeline navigation bar. Figure 4 shows a screenshot of the main GUI.

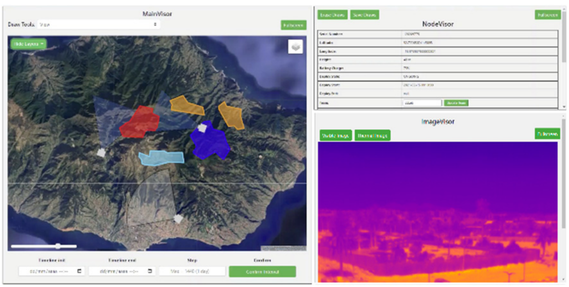

Figure 4: System's GUI with thermal image.

The real-world tests in the three Macaronesian regions started in Santiago Island (Cabo Verde), in June 2022, focusing on the mobile device itself. Around 40 participants were involved in these tests. In August 2022, the tests took place in Madeira Island where the integrated testing of the entire system was carried out for the first time, including the sensors and the two web servers. The tests in Madeira included around 25 participants. The entire system was improved based on the experience acquired, and the final test occurred in September 2022, in Gran Canaria (Canary Islands). In this last field test, participated six fire prevention and fighting experts, representing the three regions involved in the project.

The last two tests included the detection of wildfire ignitions by the system and the analysis, by the experts in fire prevention and fighting, of the: comprehensiveness and completeness of the data collected, and the functionalities of the GUI.

The feedback given both on the system's ontology and functioning was very positive, and experts did not identify any missing information.

4.4 Discussion

Our work proposes the GeMoWilDSOn, an ontology for georeferencing mobile wildfire detection and monitoring systems. We foresee that the number of different mobile sensor-based systems to detect and monitor fires will increase shortly. In our search for existing ontologies in the scope of our work, we verified that a few ontologies existed regarding fires, but none foreseeing mobile georeferencing of fires based on thermal images and terrain information. Fire Ontology (Souza, 2014) and Fire Ontology Network (García-Castro & Corcho, 2008) focus mainly, or only on fire, natural resources, and infrastructure concepts. Semantic Sensor Network Ontology (Haller et al., 2017) and Semantic Sensor Network for Forest Fire Management (Chandra et al., 2022) are primarily focused on the sensors' domain. These ontologies are somewhat generic, complex, and more of a normative kind, giving freedom for implementation. They do not easily translate to a streamlined data model that can be efficiently implemented in a real-time system where fast performance is essential and of utmost value.

Although a sensor-based approach like the one proposed by Chandra and colleagues (2022), with bases on SSN and SOSA, can be highly versatile and used in practically any domain where sensors are involved, the fact of being so generic also means it is not optimized for any particular scenario.

GeMoWilDSOn was tailored for forest fires' fight and prevention with sensors that capture images and georeferentiation. It can be easily adapted to expand the range of sensors/capabilities for other contexts, if so is necessary. Nevertheless, as it is, GeMoWilDSOn was based and is totally aligned with the classes prescribed in the sensor-based approach regarding our implementation scope, thus making our solution grounded and validated according to the state-of-the-art.

Our proposal of the GeMoWilDSOn fills the found gaps in state-of-the-art by being an ontology that encompasses both the fire and sensor domains in a streamlined way. This ontology was already validated in real tests in the field with a software system close to being completed. An important innovation and research contribution of our ontology is the possibility of complementing captured information and georeferenced polygons with manually drawn polygons to complement automatically generated information.

5 CONCLUSIONS AND FUTURE WORK

This paper presents GeMoWilDSOn, an ontology for georeferencing mobile wildfire detection and monitoring systems. We analyzed related work in the context of our practical research project for developing an innovative mobile sensor-based system with associated APIs, database, and GUI. We identified some concepts in previous work, but we needed to introduce innovative ones and simplify some views of related work. The result is a streamlined ontology focused on fire prevention and fighting with mobile sensors, specially designed for steep mountainous terrain, where firefighting can be complicated and complex. The innovative contribution of manually drawn areas of fire and shadow is of utmost importance concerning the particularities of steep terrain.

Our ontology was validated in three real-world tests where experts were delighted with captured information and its representation in the GUI of the developed system.

Our project is currently in its final stages. We are now implementing the final task consisting of a sensor location management and advisor component. With this new component, it will be possible to manually add to the system possible preferred and advisable locations to deploy the mobile sensors. Another important feature will be the possibility of the system, considering current fire and shadow areas, as well as terrain contour lines, to automatically advise changes of sensor locations, so those shadow areas (and the size of shadows) are reduced. Thus fire areas will be more clearly identified and represented. We expect to extend our proposed ontology with new concepts needed for these practical features.

Another line of future work that we foresee, in the context of a subsequent research project, is the inclusion of UAV-based sensors. Very recent developments in UAV technology in terms of stabilization and autonomy will allow the integration, in our architecture, of information provided by these aerial sensors. Hence, allowing for a completer information on fire location and evolution and improving the overall effectiveness of our system, fire prevention, and fight in general.

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