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Location-aware system for olive fruit fly spray control

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ABSTRACT

Location awareness is essential for many Precision Farming (PF) tasks with strong spatiotemporal, environmental, public health and food safety characteristics. Nevertheless, its role is much more crucial in PF tasks with efficacy depending mainly on local climate conditions and the collaboration of users. A PF task with the aforementioned characteristics is the insecticide-bait ground spraying against olive fruit fly, the most serious pest on olive cultivations. It requires location awareness, so as to be more efficient, friendly for the environment and the domestic areas, and ensure olive products with low insecticide residues. This research proposes an innovative, integrated, Location-Aware System (LAS) suitable for the ground control of the olive fruit fly. The developed system enables rapid prototyping of Location-Aware (LA) services in an intelligent PF environment combining location sensing technologies with wireless Internet, Geographical Information Systems (GIS), and Expert Systems (ES). We focus on the functional and operational capabilities of the middleware architecture, on the design issues of the developed GIS, ES, and LA modules, as well as, on the factors and infrastructure that must be considered during the spraying process. Based on this framework we developed specific LA services, such as finding the area to be sprayed, estimating the amount of the spraying solution required, canceling the spraying process, etc. These services aim in a more efficient and environmental friendly treatment. To validate the LAS a moderate-scale experiment is performed showing that the proposed system is functional and operational. LAS consult effectively the tractor attendants on how to spray, by means of reducing spraying failures and minimizing the decisions that must be taken during spraying process. Preliminary results report that with LAS no over sprayings occur, sprayings are based on infestation risk, cultivation characteristics, and meteorological conditions. Finally, a safe distance from biological cultivations, environmental protected and domestic areas is kept, avoiding pollution of these areas with insecticide residues.

1. Introduction

Olive fruit fly (scientific name; *Bactrocera oleae* or *Dacus oleae* (Gmelin), Diptera: Tephritidae) is the most serious insect pest of olive fruits in the world. It affects the olive tree cultivation causing serious qualitative and quantitative consequences with economic impacts and monetary losses (Neuenschwander and Michelakis, 1978; Economopoulos et al., 1986). Even with the pesticide treatments that are applied every year to control the olive fruit fly population, the damage caused by this insect in the fruits, results in about 10–30% loss of the olive crop (Economopoulos et al., 1982; Michelakis, 1990; Economopoulos, 2002). Without treatment and under optimum climate conditions, for the development of the olive fruit fly, the insect could infect up to 100% of the olive fruits (Athar, 2005). Control of olive fruit fly depends on either killing the hatching eggs and larvae in the olive fruit or stopping the female from mating or laying eggs. This can be accomplished with broadcast foliar sprays, or bait spraying applications using different attractants in combination with insecticides, or with massive numbers of sterile male's release. However, in real pest management conditions, bait spray from ground is considered as the most effective treatment against olive fruit fly (Manousis and Moore, 1987).

In most cases, bait sprays from the ground are performed based on the sprayer attendants' experience. As a result spraying efficacy is limited, whereas environmental protection is not taken systematically into account. Global Positioning System (GPS) technology, still in its' first steps, is now used in order to monitor the tractors and find out any failures in the spraying process. Most studies are focused on monitoring (Liebhold et al., 1993; Lyons et al., 2002) or modeling (Kapatos and Fletcher, 1983) the olive fruit fly population and adjust the spraying areas according to their findings. To the best of our knowledge, no proper attention has been given so far on the improvement of the spraying process from the research community. Note that the spraying process has spatial and temporal characteristics, which must be taken into account for an appropriate distribution of the spraying solution. For example, tractor attendants must know during the spraying process the current

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local conditions, such as temperature, wind speed, insect population characteristics, density coverage of olive trees, etc., so as to apply the appropriate quantity of the spraying solution per area unit. As a result, the success of the spraying process depends on the cultivation characteristics, insect's population dynamics and meteorological conditions. Management tools are needed for the ground sprayings against olive fruit fly because in many cases, the efficacy appears to be very limited and/or the environmental protection is almost absent. The impacts on the environment, the food chain, the operators and the natural enemies of the pests could be reduced if the ground sprays were limited to those that are necessary and conducted in an appropriate and systematic way. Clearly, this problem has all the characteristics of a Precision Farming (PF) or Precision Agriculture (PA) application and in order to find an effective solution, it is necessary to look on the new technological advances and methods offered.

The main issue in any PF environment is to provide access to electronic agro-environmental (e.g. biological, climatic, meteorological, etc.) records, namely, a step in the direction of providing accurate and timely information to farmers for the support of decision-making. Note that farms are distinguished by the distributed nature of the information, the intensive collaboration and mobility of their personnel, as well as their need to access agro-environmental information occasionally. Obviously, the aforementioned provision has motivated the introduction of ubiquitous computing technology, assuming of course that the design scenarios for developing PF systems respond to particular conditions (i.e. soil or cultivation characteristics, meteorological conditions, number of users, etc.) and demands (i.e. solving a pest problem with a specific precision). For this reason, in this research, we suggest an iterative user-centered development method to understand the bait sprayings from ground and to envision and deploy appropriate scenarios, in which the main system components respond autonomously in accordance with the context. Examples, of possible scenarios in the problem of bait sprays from the ground could be to stop the spraying activity in case the temperature exceeds a threshold or to avoid the possibility of spraying nearby an environmental or domestic area.

In many real cases, a PF environment is saturated with heterogeneous computational and wireless communication devices (Zhang et al., 2002). In addition, any service offered has to be accessible to diverse and non-specialist farmers through simple, intelligent and effortless interactions. Thus, there is a need the system to be aware of the specialized context in order to provide information and services when the farmers need them. For example, PF utilizes new information and communication technology techniques to get localized environmental conditions of the farm through the use of satellite or aerial imagery, GPS and other means (Auernhammer, 2001). The information gained is utilized for taking decisions to make environmental safe and optimal use of resources and improve productivity and quality by making appropriate use of water, nutrients, pest management, etc.

The aim of this paper is to propose an intelligent Location-Aware System (LAS) that combines location sensing technologies with wireless Internet, Geographical Information Systems (GIS) and Expert Systems (ES), for monitoring and controlling olive fly pest problem in a ubiquitous PF environment. It contributes in:

- Supporting a generic Wireless Sensor Network (WSN) model for handling heterogeneous meteorological data, managed by a simple interface (Pontikakos and Tsiligiridis, 2007).
- Providing a middleware architecture design, that allows software agents to cooperate and communicate among themselves, disseminating and/or gathering the sensory data on the WSN.
- Developing an intelligent system that integrates Location-Aware (LA) services in a ubiquitous PF environment by means of combining GIS, ES and LA modules in order to improve the efficacy of bait sprayings from ground against the olive fruit fly and minimize the consequences in the natural environment. The developed modules support tasks like the countering measures selection and the alarm spraying levels.
- Reporting some encouraging preliminary results obtained from a moderate-scale experiment, which was carried out at the province of Laconia (Greece) in order to validate the proposed system under real ground spraying conditions.

The paper is organized as follows. Section 2 provides some background information by means of the description of the problem and the related work undertaken so far. Section 3 provides the underlying methods adopted and the tools used. Details about data acquisition, the proposed architecture and the description of the experimental site, the olive fruit fly population monitoring and treatment procedures, as well as the software tools used, are provided in this section. Some preliminary results obtained from the experiment are reported in Section 4. Finally, in Section 5 the main conclusions along with the future work are presented.

2. Background

2.1. Problem description

As already mentioned olive fruit flies affect the olive tree cultivation causing serious qualitative and quantitative consequences with economic impacts. The insect is monophagous and has three to five generations per year depending upon local conditions. The flies are very mobile and have the ability to seek out cooler areas of the orchard and urban trees. Its mobility and the fact that generations overlap, make the treatment of this insect a complicated task (Manousis and Moore, 1987; Mazomenos et al., 2002; Montiel and Jones, 2002).

The olive fruit fly control with insecticide-bait spraying applications from ground consists of two phases. The first phase is the monitoring of the pest population in order to take a decision to spray or not. The number of adults in traps (i.e. McPhail traps) and observations of larval stages in fruit samples are coupled with climatic data (temperature, relative humidity, etc.) to make predictions of damages and take preventive measures. The second phase is the spraying application process itself. It aims at minimizing the population of the adult stage of the olive fruit fly with the least impact for the environment and with the lowest cost. To achieve these goals several problems need to be solved concerning geospatial, meteorological, biological and other agro-environmental data that exist during the spraying applications.

The spray process takes place during the day using tractors. Each tractor covers one section of the spraying area. The insecticide-bait solution applies in a course spray or stream to a small portion of the tree. There is no need to cover the whole tree, because the adult flies are attracted to the bait, feed on it and die. During the spray applications several problems may arise:

- During the spraying process the meteorological parameters need not to exceeded specific thresholds, defined in advance. Note that the air temperature and wind speed values are usually unknown to the spraying attendant and therefore, the spraying could continue, even in cases the meteorological conditions are inappropriate.
- Usually, the sprayings cover large areas. Thus, it is difficult for the tractor attendants to memorize their spraying areas, and as a result over or under spraying may occur.
- The spray volume dependents on the coverage of olive trees. Nevertheless, the spraying attendant cannot easily determine the

number of the olive trees per area unit. In addition, the spraying attendant cannot determine the olive fruit fly population of the spraying areas. Therefore, the spray volume per area cannot be determined at all.
- The spraying attendant is not aware of the areas inside the spraying area, which must not be sprayed for some reason (i.e. domestic or environmentally protected areas, biological cultivations, etc.).
- In addition to the spraying coverage area, the exact location of the attendant is not always known to the supervisor. Therefore, the spraying results cannot be evaluated easily.
- The problem of pattern insect population is spatially distributed. Insects are usually dispersed in a wide geographical area and the prediction of the insect population size, must maintain this spatial dimension of the problem.

Further, to avoid failures in the spray treatment a number of factors should be taken into account, such as the area of olive trees should be large enough, the population of olive fruit flies should increase significantly, the olives must be in an advanced stage, the female to male insect ratio should be greater than one, the female insects must be mature, as well as the temperature, wind speed and humidity levels should not exceed a threshold.

Finally, the requirements from the agro-environmental context may include the efficiency in preserving measures taken against the spatial dispersion of the olive fruit fly, the efficiency in ground spraying treatment, the environmental protection, the quality assurance, the reduction of cost, etc. An analysis of the most important requirements follows:

- *Preserve spatial dispersion*: A pest free area is an area in which a specific pest does not occur and should be maintained in this condition. In cases where the olive fruit fly free area is situated near or within an infested area, preventive measures and specific procedures are required for its establishment and maintenance. Efficiency in preserving measures taken against the spatial dispersion of the olive fruit fly requires the determination, establishment, verification, declaration and maintenance of the olive fruit fly free areas, as well as the consideration of the possible need for buffer zones.
- *Efficacy in ground spraying treatment*: The ground spraying treatment is about fulfilling dissimilar needs. First, offline data gathering and making it available for in-depth analysis should be fulfilled. Next, real-time reporting requirements for identifying and reporting the current environmental conditions should be considered. Finally, guidance requirements need to be examined, not simply giving answers to certain problems, but also foreseeing and forewarning about potential environmental problems. For a real-time ground spraying treatment system the main objective is to provide to the farmers improved, reliable, and adaptable services for various environmental conditions.
- *Environmental protection*: The guidelines on standards for agricultural pesticide applications and related procedures consist of detailed specifications and requirements. Application timing is influenced by meteorological conditions, which may result in physical and volatility spray losses. Temperature, relative humidity, wind speed and the possibility of rain can all affect in the efficiency of spray dispersion.
- *Quality assurance*: The quality assurance guidelines, by means of compliance with approved procedures, should include the surveillance procedures (both trapping and fruit sampling when used), regulatory controls and corrective action planning.

2.2. Related work

Much literature exists on PA technologies and applications. A comprehensive overview of worldwide development and current status of PA technologies can be found in Zhang et al. (2002). Sensor networks have been used in PA to assist in spatial data collection, precision irrigation, variable-rate technology and supplying data to farmers. One example has been the prevention of frost damage to vineyard (Burrell et al., 2004). Another example has focused on measuring the microclimate of a potato crop to deliver detailed information for decision support systems for *Phytophthora* (destructive parasitic fungi causing brown rot in plants) control (Goense et al., 2005). This involves measuring temperature and relative humidity in the crop canopy. An overview of available WSN that are applicable to agriculture and food industry has been given in Wang et al. (2006). WSN typically publish the data to the World Wide Web and allow real-time access to the data. Different types of data is collected by the sensor nodes to measure specific environmental parameters, as well as generic data, such as GPS, temperature, relative humidity, wind speed and wind direction, light, motion, etc. At the server-side the data can be visualized and analyzed within a GIS, and published via the Web to give researchers seamless access to information. GIS and geostatistical methods are powerful tools for understanding the spatial-related data, such as distribution patterns of an insect pest population (Sciarretta et al., 2001; Papadopoulos et al., 2003).

The evolution of wireless networking and mobile ubiquitous computing in combination with the advances in location sensing technologies has created the LA computing (Küpper, 2005; O'Grady et al., 2007). In this context, ubiquitous computing is a new paradigm, relying on the use of tiny devices embedded in everyday objects and environments. Due to their versatility, LA applications are able to integrate information related to geographical position, mapping, routing, searching, multimedia content and address location functionalities with user-specific profile and content. There are a wide variety of LA applications (Pontikakos et al., 2005), which are used in environmental monitoring (habitat, pollution, etc.), PA, emergency situations, navigation, industrial automation, security, advertising, etc.

LA systems need intelligent capabilities to be adaptive to farmers, reactive to context, and learn from their behavior in support of decision-making and to provide high quality services based on their preferences. In addition, they have to be able to adapt to changing access networks (Wi-Fi, GPRS, GSM, etc.) and changing environments automatically without bothering farmers or other related personnel to intervene. The LA intelligent services need to be accessed by the interesting users and specialists through simple and effortless interactions. ES (Siler and Buckley, 2005) combine the experimental and experiential knowledge of specialists to aid farmers in making the best decisions for their cultivations. Several attempts have been made to develop decision support systems and ES for optimizing agriculture operations. Support systems have been developed for weed control (Macé et al., 2007), irrigation (Srinivasan et al., 1991; Lilburne et al., 1998; Bergez et al., 2004), fertilization (Lewis et al., 2003; Bonfil et al., 2004) and pest management (Ellison et al., 1998; Mahaman et al., 2002; Cohen et al., 2008). In a pest management problem similar to the olive fruit fly problem, Cohen et al. (2008) have developed a spatial decision system for monitoring the Mediterranean fruit fly (*Ceratitis capitata* (Wied), Diptera: Tephritidae) on citrus. Their system provides recommendations to the coordinators' decisions in order to reduce the number of unnecessary spray actions and the number of sprayed plots. Although, their decision support system is flexible, it does not focus in the spraying process of each plot.

An important issue in the pest management domain, which has not been given the proper attention so far by the research community, is the development of a middleware that supports heterogeneous PF environments, processes and delivers contextual information to the farmers and simplifies any decision process concerning the agricultural practice. Software agents (Tripathi et al.,

2002) may support effectively heterogeneous systems integration and disconnected operations (Lange and Oshima, 1999). However, this technology has shown difficulties when used for managing Web content (Hendler, 2001). Integrating agents and Web services (Bellavista et al., 2005) could be considered as an alternative to cope with some of the challenges of intelligent agro-environmental monitoring and control systems, including PF environments and problems related with the pest management, such as the control of olive fruit fly by ground spraying operations.

3. Materials and methods

3.1. Data acquisition

During the knowledge acquisition process, biological and climatic data about insect population must be collected. Monitoring of adults in traps and observations of larval stages in fruit samples are coupled with climatic data in order to make predictions of damage and take preventive measures. Usually, climatic data is collected through automatic agro-climatic weather stations, which are capable of recording and storing large quantities of such data, and transmit them wirelessly to a collection point. The framework of a four-tiered WSN architecture to transmit the data from an array of sensors to the server, through their cluster heads and field-zone gateways, using a two-way data stream over a wireless link is provided in Pontikakos and Tsiligiridis (2007). Note that lessons on the deployment of sensor networks to PA are provided by many researchers in the field (Burrell et al., 2004; Goense et al., 2005; Wang et al., 2006), aiming at enhancing the efficiency and growing of cultivations. Further details of the functions and operations offered by the WSN used will be provided in a future work; however, it should be noted that the WSN combines many time critical functions, such as constant environmental sensing, data gathering and storage, computation, processing, reliable communication through a wireless medium, event detection and reporting.

It is worth mentioning that data acquisition, by means of comprehensive knowledge of the factors affecting the control process against olive fruit fly, as well as the biological cycle of the insect is a very important issue for controlling efficiently and in an environmental friendly way the ground spaying applications. These factors, outlined in the following sub-sections, are spatial, temporal or spatiotemporal in nature and they are shown in Table 1.

Table 1
Factors that must be considered during the spraying process.

Factors	Structure	Type
Geographic		
Location models and coordinates	Points	Spatial
Road network	Lines	Spatial
Spraying area	Polygons	Spatial
Slope	Contour Map	Spatial
Tracking paths	Points	Spatiotemporal
Biological		
Insect population	Contour Map	Spatiotemporal
Pest management models	Model	Spatiotemporal
Soil		
Soil type	Polygons	Spatial
Soil temperature	Contour Map	Spatiotemporal
Soil compaction	Polygons	Spatial
Soil moisture	Contour Map	Spatiotemporal
Meteorological		
Air temperature	Contour Map	Spatiotemporal
Air humidity	Contour Map	Spatiotemporal
Wind speed	Contour Map	Spatiotemporal
Cultivation		
Olive trees	Points	Spatial
Olive cultivars	Categories	Spatial
Coverage with olive trees	Polygons	Spatial
Olive size	Categories	Spatial
Olive hardness	Categories	Spatiotemporal
Olive coloration	Categories	Spatiotemporal
Environmental		
Water courses	Polygons	Spatial
Environmentally protected areas	Polygons	Spatial
Domestic areas	Polygons	Spatial
Biological crops	Polygons	Spatial
Operational		
User profile	List	Database
Equipment characteristics	List	Database
Spray solution specifications	List	Database

3.1.1. Geographical features

Geographical features are collections of themed information layers that can be used together. Each geographic feature has attributes that identify and describe it. These attributes are classified as counts, amounts, ratios, categories and ranks, etc. The most important geographic features that must be taken into account are given below:

- *Location models and coordinates*: The proposed architecture supports symbolic and geometric location models. It also provides the functionalities needed for both, the location awareness designer of the services offered, as well as the end users, such as the tractor attendants, the farmers, or other involved personnel. In geometric location models there are three coordinates: latitude, longitude and altitude. Several issues are involved in choosing a map coordinate system, including the location and the size of the spaying area, etc. In this study the World Geodetic System 1984 (WGS 84) coordinate system was used.
- *Road network*: Road networks are used to optimize the navigation during the spraying process and minimize the duration of this process. They were designed and extracted using digital ortho-rectified aerial pictures of the study area. In case there is no road network in the fields, it is assumed that there is a virtual road network that tractors could use to move in the spraying area.
- *Spraying area*: This feature gives the location and the size of the olive trees area, which has to be sprayed by each tractor attendant or individual farmer. The procedure adopted avoids over or under spray occurrence. The spraying areas were designed and extracted using the same digital ortho-rectified aerial pictures, as in the case of road networks. The characteristics of each spraying area were determined by field observations.
- *Slope*: This feature is a measurement of the grounds' surface steepness. If the ground surface of the spraying area is too steep then it is likely the spraying in this area to be performed by an individual farmer rather than a tractor attendant. The slope contours were extracted from ortho-maps of the study area.
- *Tracking paths*: The tracking paths (or tracklog layers) monitor the speed and location for each tractor attendant or individual farmer. Based on these paths a real-time calculation of the area and the number of trees that have been sprayed by each tractor attendant or individual farmer can be achieved.

3.1.2. Biological data

Insect population: Knowledge of insect population and population dynamics is essential for taking decisions, such as when to spray, which areas to be sprayed and what spraying density is going to be used. Olive fruit fly population is determined by monitoring the adults in traps (i.e. McPhail traps) and observing the larval stages in fruit samples. The data needs to be collected in real-time and includes the number of adult females, the number of adult males, the infestation degree and its' distribution in the fields, etc.

Pest management models: Pest management models for olive fruit fly are based on relations between climate conditions, insect population, yield loss or damage and economic parameters. On a pest management system Kapatos and Fletcher (1983) have used ecological criteria to model the olive fruit fly population dynamics.

3.1.3. Soil data

Olive fruit fly is possible to complete its pupal stage in the soil. Therefore, knowledge of pupation depth of the olive fruit fly in nature is an important factor to determine the degree of infestation in an area. Four abiotic factors influence the pupation depth of the olive fruit fly. These factors are the soil type, the soil temperature, the compaction and the soil moisture.

3.1.4. Meteorological data

Air temperature: According to Kapatos and Fletcher (1986) the olive fruit fly survives best in cooler coastal climate, but is also found in hot, dry regions. Temperature relationships and developmental thresholds for olive fruit fly are given in Rice (2000). The optimum temperature for the insect development is between 20 and 30 °C. High temperatures (35 °C or more) are detrimental to adult flies and to maggots in the fruit. The adult activity is approximately at 15.5 °C. High temperatures in the range 38–41 °C are detrimental to adult flies and to immature stages in fruit. The air temperature during the spraying process must be between 12 and 28 °C. The developmental temperature thresholds are different among the biological stages (egg, larva, pupa and adult) of the insect.
Air humidity: Olive fruit flies survive best in more humid climates. Also, they infest fruits in olive trees that are grown in dry regions.
Wind speed: The air speed during the spraying process must be less than 8 m/s. High air wind speed inhibits the insect flights. As a result the olive fruit flies are not fed by the sprayed solution and survive.

3.1.5. Cultivation data

Olive cultivars susceptibility: According to Neuenschwander et al. (1985) there is a range of susceptibility among different olive cultivars. The size of olives is considered as one of the most important factors. There is a positive correlation between infestation levels and olive sizes. As a result, infestation is higher in large olive sided cultivars than one bearing small olives. Olive hardness is another important factor determining the infestation levels. There is a negative correlation between infestation and hardness. When olives reach their final sizes they become softer. The olive coloration seems to play a role in infestation. For example, green olives are more susceptible than brown ones.
Coverage with olive trees: The coverage density of the olive trees in the spraying area is important for the determination of the distribution of the sprayed solution.

3.1.6. Environmental data

The knowledge of the exact location of water courses, of the domestic or environmentally protected areas, as well as of the biological crops areas is very important in order to determine the appropriate buffer zones between the sprayed and non-sprayed areas.

3.1.7. Operational data

Operational data includes user profile, specific equipment characteristics (size and power of the tractor, sprayer's specifications, etc.) and spray solution specifications (dosage, method of usage, precautions, etc.).

3.2. System architecture

This section presents the architecture of the developed LAS, which utilizes software agent technology as well as Web-services, and integrates GIS, ES and multimedia technology in order to develop and implement ground spraying control services for olive fruit fly. The LAS is able to gather data in a systematic way and making it available for in-depth analysis in order to identify and report the current environmental conditions, as well as to foresee and warn about potential problems. For this, a number of software agents are developed and included in the LAS so as; to invoke automatically the appropriate Web services, to manage offline tasks, such as preparing and converting the data that are going to be sent to the server, to monitor the spraying actions, such as when and where a spraying occurs, to manage multimedia content, i.e. execute voice actions for a decision of the ES or present an image to the device screen, and finally to synchronize the LAS components functions. Note that agents (Gervais et al., 2004) and XML Web services (W3C, 2008) can assist users (farmers and the involved personnel) in a range of different ways; they hide the complexity of difficult tasks, they perform tasks on the users' behalf, they can train or teach the user, they help different users to collaborate, and they monitor events and procedures.

The developed Web services of the LAS are used so as:

- To provide authentication–authorization.
- To download the appropriate software agents and multimedia content (digital images, voice commands, etc.) to the user device (Pocket PC).
- To update the meteorological data, the user interface, the GIS data, the ES and the Knowledge Base (KB) of the ES, etc., to the client.
- To send the supervisors' messages to the Pocket PC.
- To send the data about the spraying process, such as track paths, spraying points, etc., to the server.
- To upload multimedia content, such as images from the Pocket PC camera, to the server.
- To decide whether a plot was sprayed efficiently.

The proposed system architecture is shown in Fig. 1. It comprises of four modules; the Communication (Com) module, the LA module, the GIS module, and finally, the ES module. Since these modules are independent of each other new modules may be added or existing ones may be modified easily, facilitating the expansion, the improvement and the usage of the proposed architecture.

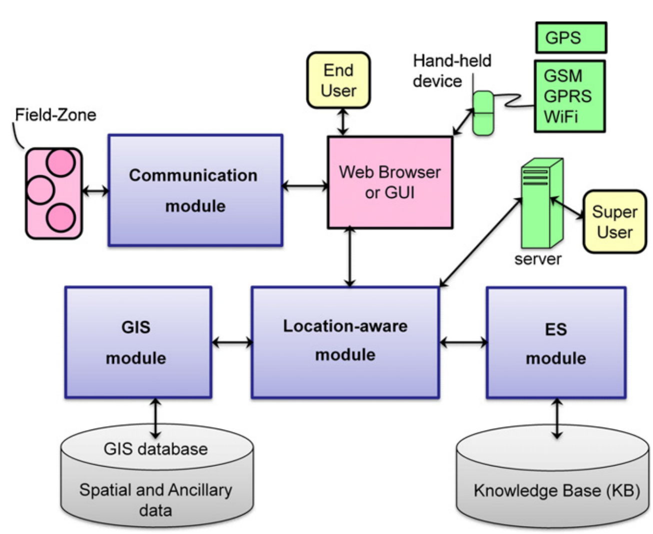

Fig. 1. System architecture.

The architecture supports symbolic and geometric location models with location awareness commands, which are responsible for the management of the functionalities of the system. The system provides an agent interface that facilitates the composition, by sending and receiving messages between agents. It involves the designer of the KB, the GIS experts, and finally the end users, namely, the tractor attendants, the farmers and the other personnel involved. The developed system offers a number of characteristics, such as: temporal continuity, reactivity, cognition, presence of agents, collaborative behaviour, mobility, location and authentication, dynamic architecture, infrastructure for developing autonomous agents, integration of agents and Web services, support for interoperability and spatiotemporal optimization.

3.2.1.1. The Com module

The Com module consists of different types of mobile agents in accordance with their functionalities, as for example, the network-based operations, the sensors' hardware, the data acquisition mechanisms, etc. It receives the required sensing data captured by the sensor acquisition devices, and performs network processing in order to facilitate query dissemination. The network operations of the Com module are distributed into four layers, each one of which is controlled by some appropriate task oriented mobile agents. Agents in each layer perform their assigned tasks by collaborating with agents of the same layer or with agents of the other layers of the Com module and transmit the processed data to their destination layer.

3.2.1.2. The LA module

The LA module coordinates all modules of the proposed application. It is responsible for the input of the objects' location into the system, the transformation of the position coordinates of the moving objects, the management of the information and the tracking layers of the GIS module described below. It combines the data provided with the location data of the objects, as well as the data provided by other components and the communication with the server, the moving clients and the graphical user interface. Also, it is responsible for the management of the tasks and the events that must be executed during the spraying process and the management of the multimedia content (images, sound, video and hypermedia). Finally, it presents the created services to the end user in a friendly Graphical User Interface (GUI) form.

3.2.1.3. The GIS module

The GIS module implements processes, such as navigation, routing, geo-coding, map representation, searching, etc. It is responsible for the management of the spatial and ancillary data. The spatial data is stored locally and can be updated using some appropriate commands. It is presented in the information layers, the number of which depends on the service and type features of the application. An information layer of a special type is the tracking layer, which stores the position of the moving objects in real-time. Ancillary data is the attributes of the spatial objects (points, polygons, etc.), the users' profile and actions, the system parameters, the sensing data, etc. The interactivity of the GIS functionality is achieved by invoking some appropriate commands (e.g. data updating, system management, browsing, multimedia management, etc.).

3.2.1.4. The ES module

The internal representation of the knowledge base contains a list of possible decisions, a list of conditions and a list of rules. The KB of the ES consists of a set of rules encoding the domain expertise. Each rule is an expression of the form:

IF ⟨conditions⟩ THEN ⟨actions⟩

Table 2
Decisions, explanations and the used data of the ES.

Decision	Explanations	Data
Spray with density "X"	Infestation levels are high	Geographic, soil, meteorological
	Infestation levels are low	Cultivation
	High infestation risk	
	Low infestation risk	
	Olive cultivar susceptibility is high	
	Olive cultivar susceptibility is low	
Do not spray	Temperature is too low	Soil, meteorological, geographic
	Humidity is low	
	This area is not your spraying area	
Go to the next plot	The area has been already sprayed	Geographic, Operational
Abort spraying process	Temperature is too high	Meteorological
	Wind is too high	
Turn left/right	Distance from a previous position is too small	Geographic

where if the conditions are true then the actions are executed. Actions could be a set of commands or decisions that send a conclusion to the working memory (i.e., spray = abort), display into the screen a user notification (i.e., abort spraying) or an image, or play multimedia content, such as sound and video. Finally, the Inference engine of the ES supports forward chaining (or data-driven) mechanisms. A list of the main decisions of the proposed system is shown in Table 2.

3.3. Experimental study

A moderate-scale experiment was conducted in order to evaluate the proposed system. The experiment was carried out between July and October of 2008 in the municipality of Monemvasia in the Laconia province (South-East Peloponnesus) of Greece (Fig. 2). The randomized complete block experimental design was used. Three regions, the villages Agios Nikolaos, Nomia and Talanta with olive tree cultivations were selected. Each region was divided in sections, and three neighboring sections were selected. Every section is more than 0.3 km^2 and has about 3000 olive trees. All sections are divided in plots with different geographical (slope, ground, etc.) and cultivation characteristics (cultivation density, cultivation variety, etc.). Each section was assigned to be sprayed by one tractor. The tractor attendants had sprayed their section at least once in the past. The first spray application in each section is the reference spray application. For comparison reasons in this first spray the attendant was not allowed to use the system, even though the tractor was tracked by it. In the next spray application of the same section the attendant consults the system in order to spray. The server of the system was located in the InfoLab of the Agricultural University of Athens, approximately 160 km away from the study area. Microsoft Windows Server 2003 was used as server's operating system. The data on the server was come from the stuff responsible for the measurements of the insect population, the Pocket PC devices of the tractor attendants, the scientists in charge, such as pest management experts, GIS experts, etc., the meteorological station that was established near by the area of the experiment and the farmers.

3.3.1. Monitoring the olive fruit fly population

The ground spraying operations for the olive fruit fly control are focused on the reduction of the adult population as it is the only stage of the life cycle that the insect is exposed. In order to monitor

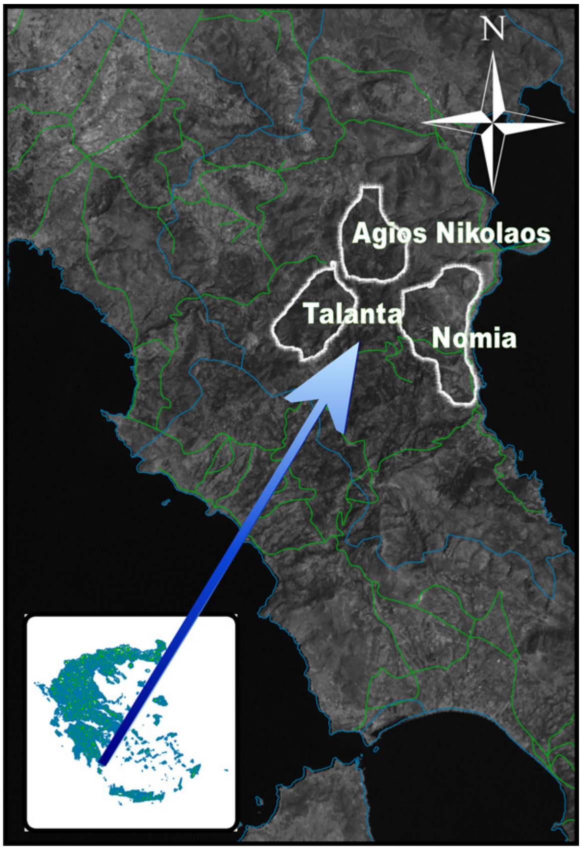

Fig. 2. The experimental regions.

the adult population glass McPhail traps where distributed in the three selected regions. Each trap is placed in the canopy of an olive tree (Fig. 3). The traps attract both adult males and females. Trained personnel monitored the traps about once a week, recorded the number of males and females per trap and imported the acquired results into the server. The acquired data was imported into the system using either appropriate Web services or by email or regular mail. In the last cases a GIS expert user imports the data on the server. At the central office (located in Sparta, the capital of

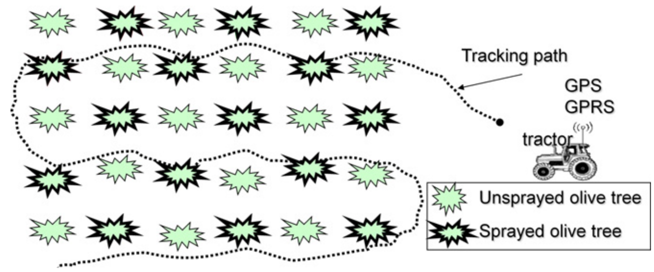

Fig. 4. The schematic display of the spraying process.

Laconia province, approximately 60 km away from the study area), the supervisor in charge consulted the server's data and decided whether to spray or not a region. However, in this experiment we focused mainly on the optimization of the ground sprayings rather than on the decision when to spray. The population per trap was used as a factor of the spraying density determination. The fixed location of each trap is determined by using GPS. The acquired traps' data for the adult's population is stored in a GIS point layer (named TRAPS). Using kriging interpolation method we estimated the infestation risk over the experimental area (Liebhold et al., 1993). The McPhail traps that were used and the point type layer of the traps information for a specific area are shown in Fig. 3.

3.3.2. Control in ground spraying treatment

Ground spraying treatment in olive trees must be performed by taking into account the WSN configuration. During the spraying process, a pre-established meteorological station, nearby the experimental site, provided temperature, relative humidity and wind speed values at 10 min intervals. For each plot the system provided the olive fly population per trap and the volume of the required spray. In each plot a tractor which carries a Pocket PC with wireless Internet access (GPRS) was assigned in each of the three sections. For a spraying to proceed the temperature must be in the range of 14–28 °C, whereas the air speed must not exceed 8 m/s. A schematic display of the spraying process is shown in Fig. 4.

During the spray application the system becomes aware of the location of the tractors in respect to the designated olive trees' area. Then, a decision about the volume and the actual spray area is made

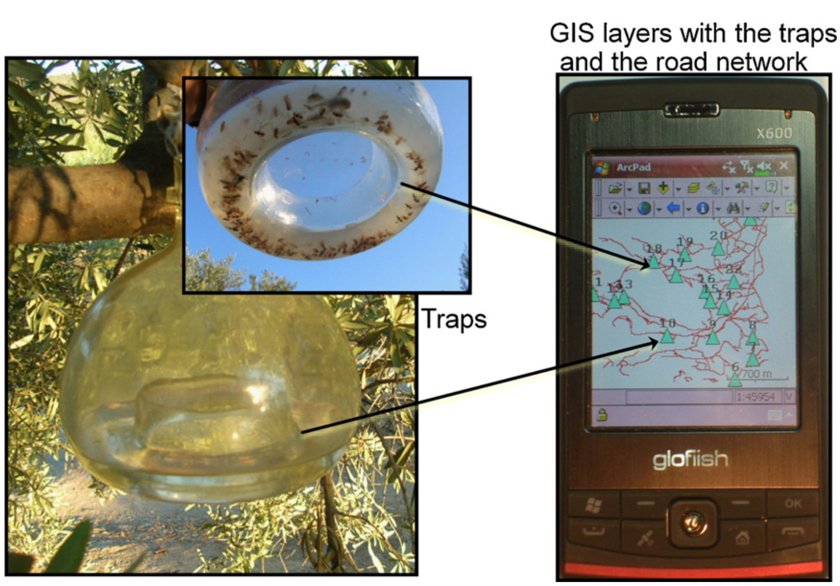

Fig. 3. Glass McPhail traps for the monitoring of olive fruit flies and the GIS layer of the trap network.

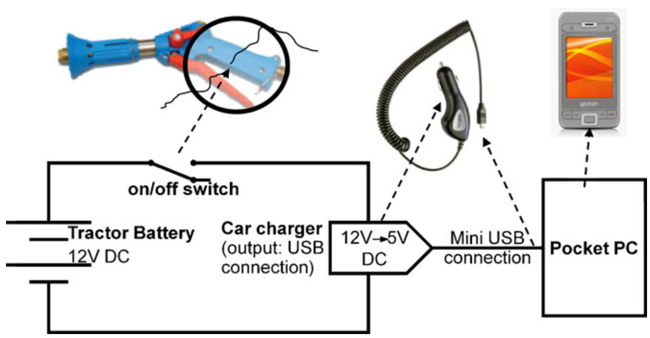

Fig. 5. The circuit used for the determination of the spaying events.

and the tractor attendant proceeds with the operation. If it is not allowed to spray the area, the ES reports to the attendant with the reason, i.e. temperature is too high/too low, wind speed is too high, etc. Note that when a tractor is in the area that is designated to be sprayed by another tractor, a location-based notification is sent to the attendant. Notifications are also sent by the system informing both the tractor attendant and the spraying supervisor when the tractor comes into an area that has been sprayed or when the tractor is nearby a protected area that must not be sprayed. In such cases, the spraying supervisor may send a notification to the involved or to all the spraying attendants. An additional capability is that the attendant may use multimedia data, such as photos of the spraying areas, sound files with advises or instructions on the spraying operation, textual information, network data concerning the spraying operation, etc. Finally, the attendant has the capability of personalizing the system, namely, to update the database, or utilize help on the system's operation.

In order to determine the location of the sprayed area, the sprayed duration, as well as the total solution volume of the insecticide applied, a simple, economic and efficient in its usage on/off switch was constructed and adjusted to the trigger of the spray gun. The circuit, shown in Fig. 5, consists of the tractor's battery, a car charger, an on/off switch adjusted to the spraying gun handle and the hand-held device (i.e. a Pocket PC). When the spraying attendant does not press the spraying gun's trigger (no spraying mode), the circuit is closed, there is flow of electric charge and the device is being charged. When the spraying attendant presses the spraying gun's trigger (spraying mode), the circuit opens; there is flow of electric charge and the charging of the device stops. The algorithm for the estimation of the spraying volume per position applied by a single tractor attendant during the spraying process in the form of pseudocode is shown below:

```
INITIALIZE previous state (=charging or not charging)
LOOP
  IF current state = NOT charging and previous state = charging THEN
    Start_time = current_time
    Start_point = current_GPS_point
    STORE Start_point, Start_time,
    previous state = NOT charging
END IF
  IF current state = charging and previous state = NOT charging THEN
    End_time = current_time
    End_point = current_GPS_point
    Duration = End-time-Start_time
    Start_End_solution = Solution_per_time*Duration
    STORE End_point, End_time, Start_End_solution
    previous state = charging
  END IF
END LOOP
```

Note that before each spraying at least three blank trails, with pure water, are performed in order to estimate the water flow of the sprayer distribution system of each tractor.

3.4. Software implementation

The system was implemented, using Microsoft Visual Studio.NET. The olive fruit fly treatment application was executed on a Pocket PC with Windows Mobile 6 operating system. For the development of the GIS module the ESRI ArcPad 7.1 was used. Simple and advanced GIS functionalities were used which are related to mapping, tracking, routing, searching, etc. The vector-based geographical data was stored as ESRI shape-files (.shp) and the ArcMap 9.2 was used to edit these files. Publishing the shape-files to the web are made through the ArcGIS server 9.2. Finally, the agents and the Web services were implemented using the Microsoft .NET Framework version 2.0.

4. Results and discussion

4.1.1. Geospatial data base

In order to integrate the GIS, ES and LA services, the LAS provides the following geospatial information layers:

- *Meteorological stations*: It provides the temperature, the relative humidity and the air speed values received from the meteorological station(s). In this experiment a pre-established meteorological station, nearby the experimental site, was used.
- *Road network*: It provides the road network of the spaying area supporting different types of road network.
- *Traps*: It provides the trap network and insect population in each trap.
- *Cultivations*: It shows the plots of each section, namely, the areas covered by olive trees that need to be sprayed. It also provides the density of the olive trees in the spraying area.
- *Tractor area*: It shows the sections to be sprayed by the tractor attendants.
- *Spray area*: It shows the boundaries of the spraying areas.
- *Infestation risk*: It provides the infestation risk of any point in the sprayed area. A detailed description of its estimation is given in the following Section 4.2.
- *Environmental protected areas*: It provides the areas, including their buffer-zones that must not be sprayed. Examples of such areas are rivers, water courses, biological cultivations, etc.
- *Inhabited areas*: It provides the inhabited areas (houses, villages, etc.) including their buffer-zones that must not be sprayed.
- *Tractor's tracking paths*: It shows the tractor's path points tracked by the GPS.
- *Sprayed points*: It shows the tractor's position and the time of the sprayings.
- *POIS*: It provides the Points of Interest (POIs). These points include textual information and multimedia content for specific areas (i.e. protected areas).
- *Olive trees canopy*: It provides in form of polygons the ground projection of the canopy of each olive tree of the experimental site. The polygons were created once, before the sprayings began, using geodetic digital maps of the experimental area.

An updated version of the above layers is downloaded in the user's device (Pocket PC) every time a spraying begins. If a new content is added the system uploads it on the server automatically, using software agents and web services. Due to the limitations of the processing capabilities of the hand-held devices and the relative high computation power that the GIS system demands, the GIS layers are displayed and managed automatically. The system performs all the appropriate adjustments (i.e.

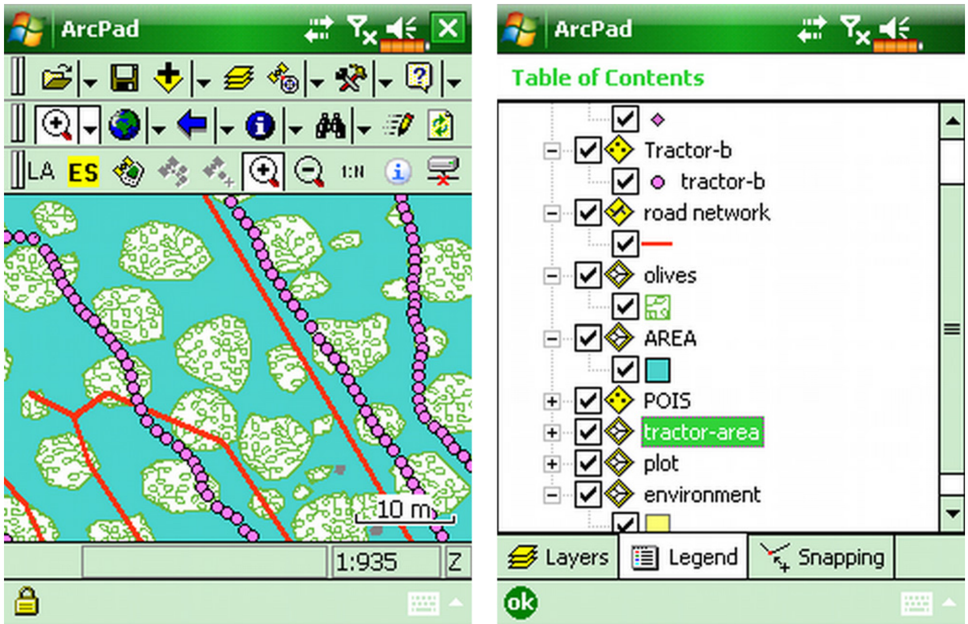

Fig. 6. The GIS interface on a Pocket PC.

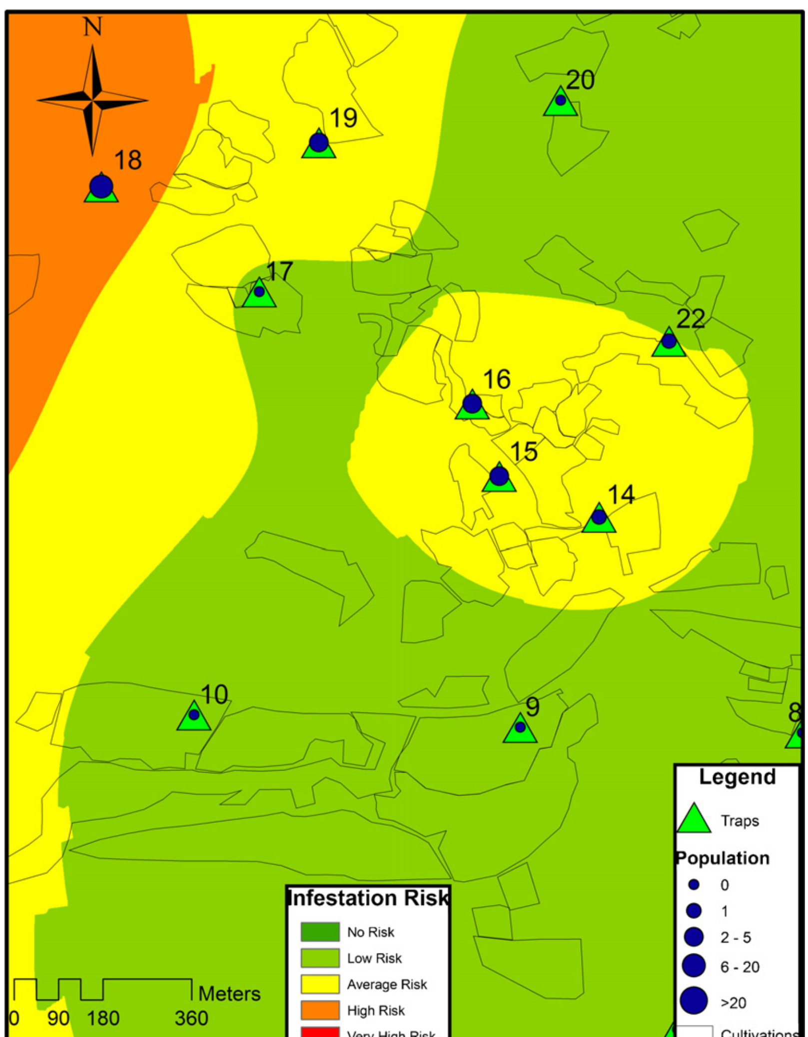

Fig. 7. Infestation risk for a specific region in a particular day.

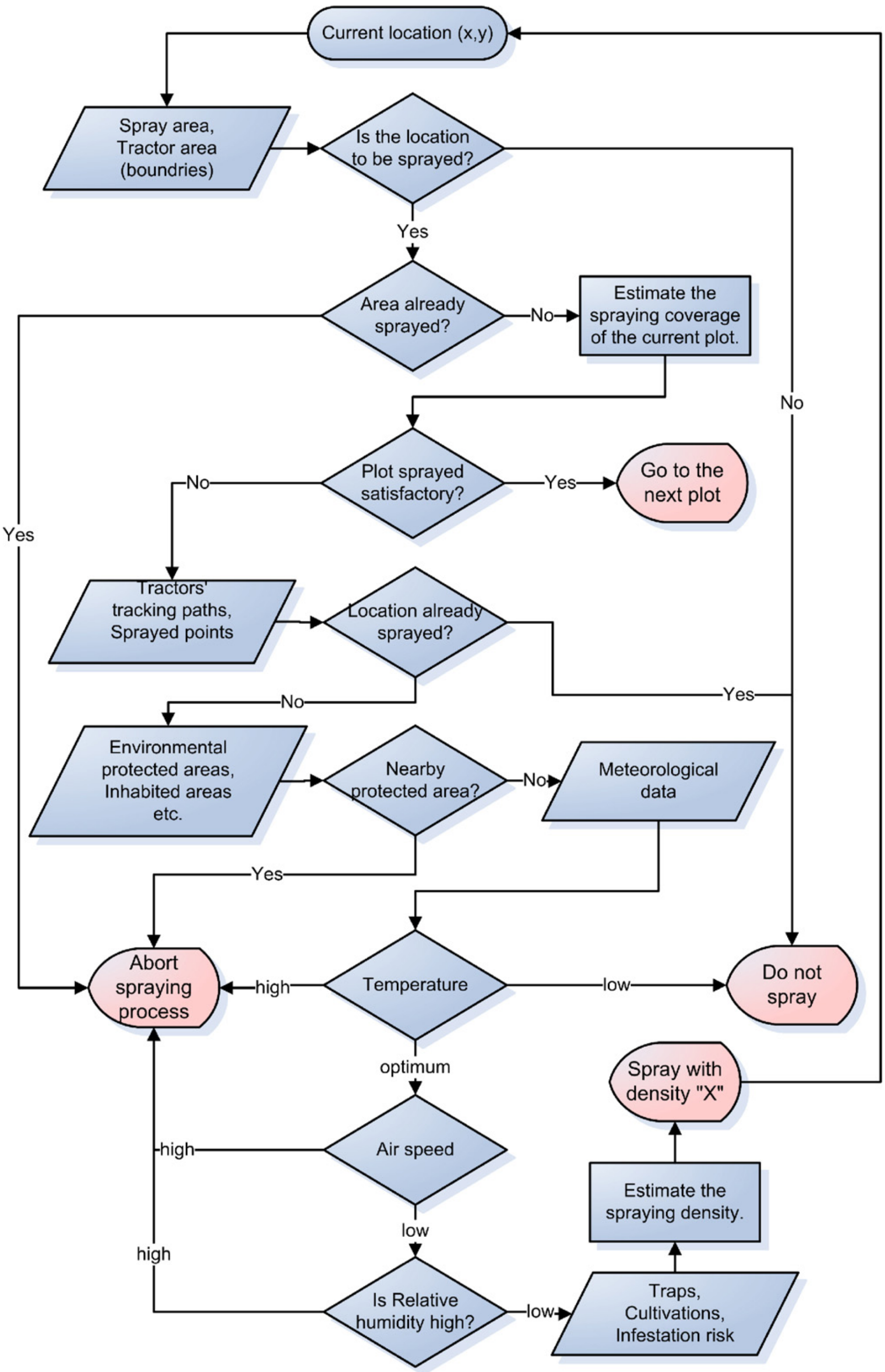

Fig. 8. The decision process.

navigation, map scale, zoom in, zoom out, etc.) including data updating. Thus, the GIS layer is displayed in the device screen only when it is necessary, i.e., it gives significant information to the user. The same approach is used in the communication of the device with the server. For example, the data that is not altered during the spraying process is uploaded on the server or it is downloaded on the device less frequently. Fig. 6 shows the GIS interface.

4.2. Modeling the infestation risk

The decision about spraying in a specific region is based on a number of criteria, concerning the trapped population, namely, the population of olive fruit flies should be increased, the female to male insect ratio should be greater than one, and the number of the flies' population should exceed a threshold (more than 5 flies per trap).

The infestation risk (*INFR*) is modeled using the following algorithm:

```
FOR EACH trap LOOP
  IF f + m>20 THEN INFR = 3
    ELSE IF f + m>5 THEN INFR = 2
      ELSE IF f + m>0 THEN INFR = 1
        ELSE IF f + m = 0 THEN INFR = 0
    END IF
    IF f > m THEN INFR = INFR + 1
END LOOP
```

where m, f is the number of male and female adults of the insect, respectively. The *INFR* = 0, 1, 2, 3, 4 corresponds to the symbolic states of "No Risk", "Low Risk", "Average Risk", "High Risk", and "Very High Risk", respectively. Based in the above algorithm raster GIS layers are developed, using kriging methodology. In order to support the decision process during the spraying, the last kriging layer (taken before the spraying process) was used. The infestation risk for a specific region in a particular count is shown in Fig. 7.

4.3. Decision process for the spraying

The spraying attendant cannot easily determine the number of the olive trees per plot and therefore cannot estimate easily the spray volume per plot that must be sprayed. The system provides the information about the coverage per plot, the olive cultivar susceptibility, the meteorological conditions etc. Then the system notifies the attendant to spray with a specific density, i.e. "Spray with density 3" and give simple explanation: "Spray every third tree". Otherwise, the system notifies the attendant with an action, i.e. "Do not spray". The decisions are shown in Table 3 and the decision process of how to spray a specific location is shown in Fig. 8. In addition, the attendant is not aware of the restrictions concerning the spraying and non-spraying areas. For this case while the tractor approaches the system informs the attendant about the spraying process without preventing him from differential spraying actions. Nevertheless the system informs the supervisor about this situation. In a future work we intend to use some kind of device so as to block such actions.

The user interface displays the ES results in a form of text actions, voice orders or image notifications (Fig. 9). It is simple and has easy to use customizations. Even though the ES could provide a detailed explanation of the system's reasoning, for simplicity reasons, a more abstract and specific explanation scheme was used. Instead of using the conditions of the rules that had been fired and display these conditions to the user's screen, we used for each final conclusion a set of explanations that the user easily understands. The above scheme hides the complexity of the system's reasoning and is tailored to the end user needs. For example if the final conclusion is *Spray* = "*abort*" and the reason is because *Temperature* = "*high*" then the explanation action is DISPLAY (text, "Temperature is too high!"), namely, displaying to the user's screen: "Temperature is too high!".

The actions, which are commands or decisions, are used in order to display into the screen a user notification (i.e. abort spraying) or an image, or play multimedia content, such as sound and video. An example is as follows:

```
IF Temperature = "high" THEN
  spray = "abort"
  DISPLAY(text, "Temperature is too high!")
  DISPLAY(text, "Abort spraying")
  DISPLAY(image, "\abort.jpg")
  PLAY(sound, "\abort.wav", 3 times, interval = 3000 ms)
END RULE
```

Table 3
Decisions and explanations of the ES.

Decision	Explanation
Do not spray	The area has been already sprayed
	This area is not your spraying area
	Nearby protected area
Spray with density "X"	Infestation levels are high
	Infestation levels are low
	High infestation risk
	Low infestation risk
	Olive cultivar susceptibility is high
	Olive cultivar susceptibility is low
Abort spraying process	Temperature is too high
	Wind is too high
Stop spraying process	Temperature is too low
Go to the next plot	The plot is already spayed

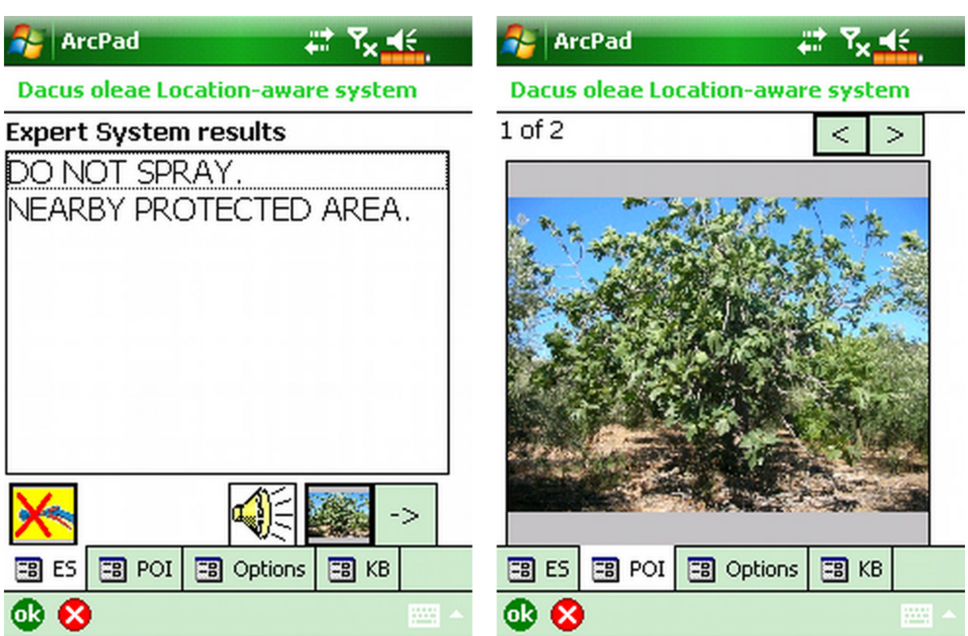

Fig. 9. ES interface.

Fig. 10. The spraying process.

In past, GPS technology was used in order to monitor the tractor's tracking paths and impute responsibilities for any failures to the attendants. However, there is an important difference between the proposed system and those attempts. As we have already explained in detail the system consults the attendants on how to spray and reduce any spraying failures by simply following the decisions of the system. Many of the attendants considered that they perform the spraying by an almost perfect way. This study has shown that the attendants ignored their own spraying failures (double spraying areas, spraying of protected areas, etc.). The proposed system reduces the number of decisions that must be taken. The spraying process is shown in Fig. 10.

Some of the tractor attendants proposed certain improvements, such as the use of hand-held devices with higher screen size and bigger font size. Although, in most LA cases, hand-held devices with low screen size is considered an advantage, in the ground sprayings it is considered to be a drawback, mainly due to the rough surface (rocks, rugged roads, off-road driving, etc.). This problem could be easily solved by using Pocket PCs with wide range screens, Tablet PCs or Laptops. The decision messages were in English and the attendants in this experiment which were all Greeks, suggested their own language as a better choice for them. However, the choice of the English language did not cause any real problem or difficulty to tractor attendants because they were young with acceptable level of English and the text messages were quite simply. Nevertheless, one should be taking into account, that in many cases the attendants are not Greeks as well. Therefore an international language, such as English, was used to display the text messages on the screen. In a future work we intend to solve this issue by providing to the users with the capability to choose their preferable language interface. Note that, the attendants for the voice notifications could have chosen between English or Greek language.

4.4. System effectiveness to improve the spraying process

As mentioned in Section 2, the spraying areas cannot be memorized by the tractor attendant and therefore over or under spraying might occur. The over spraying could occur when the same tractor attendant sprays with higher density or sprays more than once a specific area. Also, it may be occurred when different tractor attendants spray the same area. Fig. 11 shows a reference spraying (without LAS) and a treatment spraying (with LAS). In the first case two tractor attendants sprayed the same plot while in the second case the area was sprayed by the designated attendant only. For simplicity reasons only the tracking paths of the tractors, the road network, and the cultivation layers are shown. In cases with LAS no double spraying occurred, while in cases without LAS several over sprayings were noted. In addition, without LAS some biological cultivations were sprayed while with LAS no such an issue occurred. Furthermore, without LAS sprayings occurred nearby domestic or

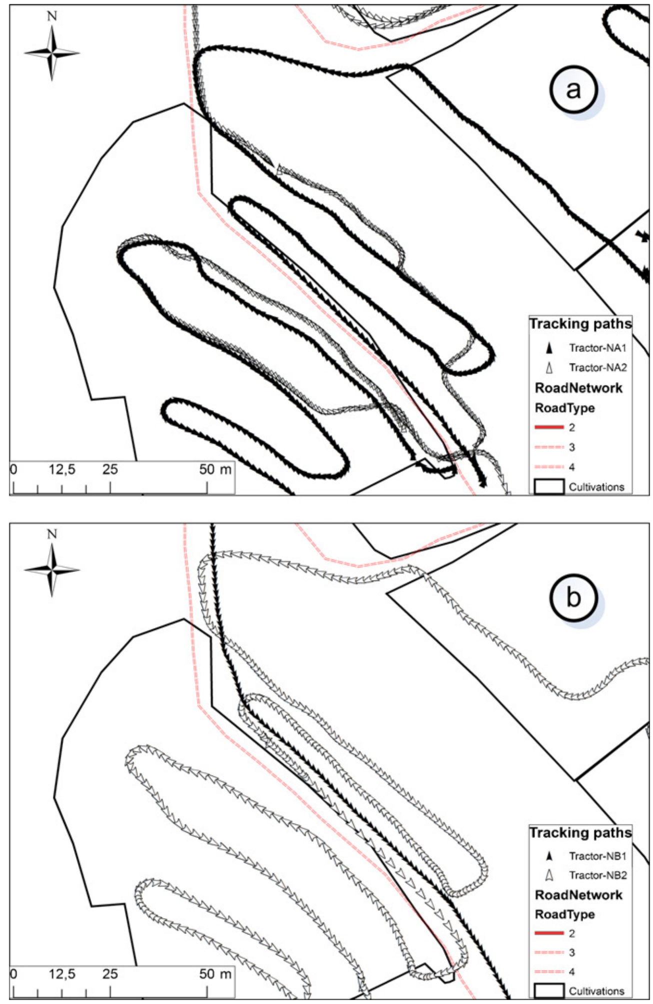

Fig. 11. (a) Reference spraying: The same area sprayed by two tractors (duplicate spraying). (b) Non-reference spraying: The same area sprayed by the designated tractor (single spraying).

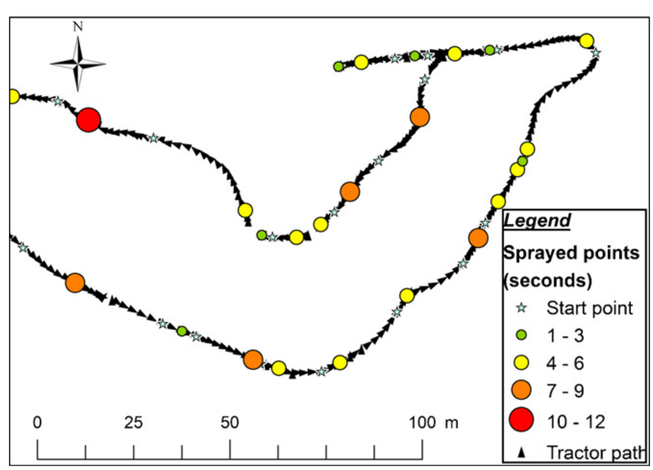

Fig. 12. Sprayed points for a specific area.

Table 4
Experimental findings: without LAS and with LAS.

Parameter	Without LAS	With LAS
Over sprayings	Several over sprayings were noted. Tractor attendants sprayed their area more than once or sprayed the area assigned to another tractor attendant	No over sprayings occurred
Sprayings in or nearby biological cultivations	Some biological cultivations were sprayed or sprayings occurred nearby biological cultivations	Biological cultivation was not sprayed. A safe distance from these areas was kept
Sprayings nearby domestic areas	Sprayings occurred nearby domestic areas	A safe distance from these areas was kept
Sprayings in or nearby environmentally protected areas	Sprayings occurred nearby environmentally protected areas	A safe distance from these areas was kept
Spraying density	Subjective sprayings occurred, i.e. high (low) volume solution, in areas with low (high) olive fruit fly population was applied	Sprayings were based on infestation risk and cultivation characteristics
Spraying duration (gun trigger)	Higher than the proposed by official regulations	As proposed by official regulations
Meteorological conditions for spraying	Several violations were noted	The sprayings were based on meteorological data

environmentally protected areas. On the other hand, with LAS a safe distance from these areas was kept.

Using the circuit and the methodology prescribed in Section 3.3.2, we derive an estimate of the location, the duration and the volume of the insecticide applied. Fig. 12 shows the sprayed points of a specific area. The layer of these points is uploaded frequently in the server, so as to be visible by anyone interesting. In addition, this layer is used to avoid double spraying in an area.

Finally, the most important findings drawn from the experimental use of LAS are presented in Table 4.

5. Conclusions

In this work we proposed a LAS suitable for PF applications, such as the bait spraying control of the olive fruit fly. Spray applications from the ground seem to be the most appropriate treatment. However, during the spray operations there are several problems that the existing approaches do not solve. The spraying is heterogeneous and should be aware of the specialized context, in order to provide information and services whenever farmers and tractor attendants need them.

There is a wide variety of LA applications utilizing specific location sensing capabilities; however, the realized one has the property to combine enabling technological advances in Internet, wireless communication with GIS, ES and multimedia systems. It also integrates many interesting middleware architectural characteristics, such as, the independence of the positioning system, the location model support, the LA decision support, the user friendly environment with multimedia capabilities of the GUI and the flexibility in the development of new LA applications and services, etc. The developed middleware architecture adapted future technologies, encapsulating and integrating various modules as agents and web services. The proposed system enables the creation of large-scale, outdoor, widely distributed, heterogeneous networked embedded systems that inter-operate and adapt to their environments. It has been deployed and validated in a moderate-scale region of Greece (Lakonia province). The preliminary results showed that the system's architecture was functional and operational. As for the improvement in spraying process, it is accomplished by the developed modules, the modeling of the infestation risk and the decision process for the spraying. The validation showed the effectiveness, reliability, flexibility and the low cost of the deployment.

Future work includes detailed geo-statistical analysis of data obtained by the full deployment of the system, development of new Web services and tools, as well as, its extension in other similar pest problems.

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