A Proactive System For Maritime Environment Monitoring

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Abstract

The ability to remotely detect and monitor oil spills is becoming increasingly important due to the high demand of oil-based products. Indeed, shipping routes are becoming very crowded and the likelihood of oil slick occurring is increasing. In this frame, a fully integrated remote sensing system can be a valuable monitoring tool. We propose an integrated and interoperable system able to monitor ship traffic and marine operators, using sensing capabilities from a variety of electronic sensors, along with geo-positioning tools, and through a communication infrastructure. Our system is capable of transferring heterogeneous data, freely and seamlessly, between different elements of the information system (and their users) in a consistent and usable form. The system also integrates a collection of decision support services providing proactive functionalities. Such services demonstrate the potentiality of the system in facilitating dynamic links between different data, models and actors, as indicated by the performed field tests.

Introduction

Oil pollutions impact the environment, the economy and the quality of life for coastal inhabitants. The increasing importance of petroleum products raised the concern on maritime safety and environmental protection, leading to a greater interest in frameworks for remotely detecting oil spill at sea (Abascal et al. (2010)). Several technological advances were made, especially under the propulsion of catastrophic events (Balseiro et al. (2003), Janeiro et al. (2014)). Nevertheless, most of the approaches have been focused on large oil spills while smaller ones and operational discharges in regional area have received somewhat less consideration, despite their importance in the routine work of local authorities, especially in protected areas of great environmental value (Ferraro et al. (2009)). In addition, classical remote sensing frameworks can be enriched by adding information collected in situ thanks to static and mobile sensors and leveraging on innovative methods for data correlation and fusion (Guo and Wang (2009), Jordi et al. (2006)).

In this work, we aim at addressing these issues by proposing an integrated and interoperable system based on advanced sensing capabilities from a variety of electronic sensors along with geo-positioning tools, yet suitable for local authorities and stakeholders. In particular, the proposed Marine Information System (MIS) integrates multispectral aerial data, SAR satellite processed data, environmental data from in situ monitoring stations (e.g. buoys), dynamic data acquired from in situ mobile sources, such as volunteers and Autonomous Underwater Vehicles (AUVs) .

The MIS is enriched with a collection of environmental decision support services, for i) automatically screening the overall situation, ii) quantitatively representing risk factors and iii) proactively notifying events that deserve the consideration of end users.

A model for the computation of dynamic risk maps has been included, by aggregating the available heterogeneous data source ranging from maritime traffic density to water quality parameters sensed by electronic noses. Visualization of the risk map provides a quick yet effective way to have an outlook of the situation in the monitored area, while its automatic analysis – performed by intelligent agents – allows the delivery of proactive alerts to local authorities in charge of monitoring.

The proposed system has been demonstrated during extensive test exercises held at the National Marine Park of Zakynthos and at National Park of Tuscany Archipelago in the framework of FP7 Project Argomarine.

The paper is organized as follows. In the next session we recall the architecture of the designed MIS, describing its components and features. Then methods for the real-time assessment of risk based on the heterogeneous data collected into the MIS are introduced. We next describe the proactive services capable of exploiting the computed risk maps for issuing alerts to local authorities. Finally we discuss the test fields performed for the validation of the proposed model and we conclude the paper with ideas for further improvement.

Architecture of the Marine Information System

The MIS has been designed to provide an effective and feasible detection and management of marine pollution events, by integrating and analysing data acquired by a number of monitoring resources, exploited to get useful and relevant information about the controlled sites. The main task of the MIS is to serve as a catalyst for integrating data, information and knowledge from various sources pertained to the marine areas of interest, by means of adequate Information Technology tools. More precisely, the MIS has been conceived as a connected group of subsystems for performing data storage, decision-support, data mining and analysis over data warehouses, as well as a web-GIS portal for the access and usage of products and services released to end-users. Products are herein considered as the marine environmental data acquired by the system or result of their processing; while the services are the processing facilities supplied by the system.

The system has to deal with all these kinds of knowledge for being effective and useful in *the environmental management process* (Cortes et al. (2000)), which typically consists of four activities in the following order hazard identification, risk assessment, risk evaluation and intervention (Fedra and Winkelbauer (2002)).

The MIS has to be very effective in managing and organizing quick solutions to severe and complex environmental problems. Such problems need, due to their multidisciplinary and heterogeneous nature, in order to be solved, the cooperation of many different subsystems which must be integrated, for a wide and more complete view and understanding of the specific situations.

The specific MIS requirements, first of all, take into account all the acquisition sources that are available and used within the monitoring activities, and belonging to specific technological devices, as well as the archiving and storage systems. In order to develop the MIS following INSPIRE and GMES recommendations (INSPIRE (2007)), the modalities to communicate and interact among systems, and in general to and from the system have been reviewed. Regarding in particular an efficient management of the information flow within the system, needed for guaranteeing interoperability among the different components. Hence the MIS is designed including as a set of specialized subsystems cooperating among each other.

MIS architecture was designed with independent and re-configurable units in order to guarantee interoperability and portability to the MIS, meaning that single units could be re-designed, or its internal components could be modified to fit to specific different domains of application (or case study), without the need to re-design the whole architecture (Pieri et al. (2012)).

The MIS architectural design is shown in the following Fig. 1, where the composing units are represented, along with the communication paths that exist and are needed for the MIS to work.

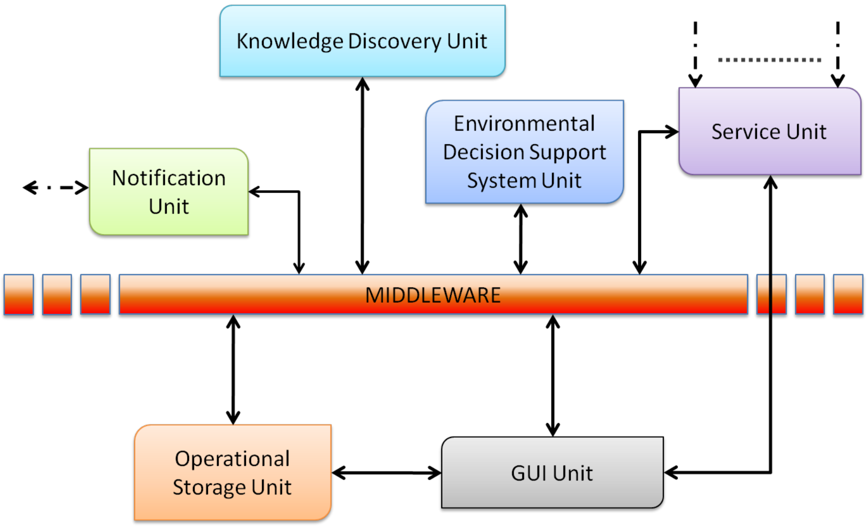


Fig. 1: Architectural design of the MIS with modular structure evidenced.

The MIS intelligence is represented by the Environmental Decision Support System component (EDSS) which is responsible of the detection and monitoring of pollution accidents by analysing and combining the multisource data coming from the different data acquisition and processing subsystems of the MIS.

The design of the EDSS required understanding of the environmental problem domain and identifying the domain experts and authorities to cooperate with. Particularly important has been the identification of the problems to be solved by exploiting the EDSS aid, and how the system can intervene and improve the current oil spill detection and management procedures. According to these results, the EDSS has been conceived according to a three levels structure, i.e. by endowing it with three main functionalities:

1. Data Gathering
2. Diagnosis and/or Prediction
3. Decision Support

1. Data Gathering. As typically happens, the EDSS has to cope with very different types of data, which can arrive even in real time from a variety of sensors. Indeed, data are gathered from various monitoring resources and consist of:

- SAR images and interpretative reports;
- Hyperspectral images from airborne sensors and interpretative reports;
- Data collected by buoys;
- Data collected by underwater autonomous vehicles;
- E-nose data;
- Forecast data obtained by applying simulation models;
- Data about the maritime traffic through AIS systems;
- Data reported by sailing volunteers.

The heterogeneity of these data has suggested distributing the interpretation task among different modules that nominally correspond to different subsystems of the MIS. Results of the interpretation are stored within the MIS, in dedicated databases, and are used by the EDSS for the other two functional levels.

2. Diagnosis and/or Prediction. Risk analysis models are applied for diagnosis and prediction. In particular, the environmental data acquired by the various monitoring resources are fused for site characterization and observation, in order to detect possible marine pollution events.

3. Decision Support. Support to decisions is, finally, supplied by drawing an optimized plan of exploitation of the resources available for monitoring and of the processes for data analysis, so as to confirm the detection of the event and issue an alarm. Suitable presentation and documentation of alarms are supplied along with feasible EDSS suggestions aimed at supporting the feasible event management and recovery interventions.

According to this conceptual model, the EDSS has been designed as composed by two main components: the Risk Analysis Model and the Resource Management Service.

These have been modelled in order to assure a number of desirable features, such as:

- ability to acquire, represent and structure the knowledge in the specific domain under investigation
- ability to separate data from models, in order to be re-usable
- ability to deal with geo-referenced data
- ability to provide expert knowledge related to the specific domain
- ability to be used for planning, management and alerting
- ability to give the end-users (both on the manager/experts side, and the external users) assistance for interfacing with the system and selection of resolution methods.

Methods for real-time risk estimation

The goal of this section is to introduce methods for the provision of real-time risk assessment, in order to produce a snapshot of risk in the region of interest which can then either i) automatically exploited by proactive services (as explained in the next Section) or ii) be directly analysed by stakeholders helping them to keep the threat to safe navigation and natural environment as low as reasonably practicable (ALARP).

In classical quantitative risk assessment, a global risk estimate is derived by multiplying the likelihood of occurrence of adverse consequences by the magnitude of each consequence (see Cocco et al. (2011)). Extending this principle, we aim at devising a method for the computation of a local risk estimate for each point in a geographical region of interest. The computed point wise estimates can then be gathered and represented in a thematic map of risk for the given region.

Among the data integrated into the MIS, a selection has been made to extract those parts of information which might be relevant in risk analysis for the control of oil spills and other pollution events. They are related to maritime traffic, oil spill reports from remote sensing, in-situ observations, volunteer reports and local monitoring coverage. Each of the above data corresponds to a summand in the overall risk assessment as explained in the following sections.

Maritime traffic

Since maritime traffic density is very potential in contributing ships accidents and consequent spills, traffic information derived either by real-time AIS messages and by remote sensing images has been included (Magrini et al. (2013)). Beside vessel position which is mandatory, the speed over ground, the course and the typology (e.g. cargo, tanker, and passenger ships) are also considered when available. The distance among vessels has not been taken explicitly into account but it is modelled implicitly. Indeed, a Kernel Density Estimation (KDE) approach has been followed (see (Laxhammar et al. (2009)) for an application of KDE to maritime traffic). In this approach, each vessel v having position p_v contributes to an increase of traffic-related risk R_{tr} in a region around p_v whose shape and modulation are determined by a kernel function K. The traffic-related risk R_{tr} in the point q at time t can be written as:

$$\mathbf{R_{tr}(q, t)= \textstyle\sum_v w_v \cdot K(p_v, q)} \tag{1}$$

where the sum runs over all the vessels which reported their position in the time window $[t-\tau, t]$ where τ is a configurable parameter, and w_v is a weight associated to v depending on the vessel speed, course and typology. As for the kernel K, a common option is to use a Gaussian kernel, although non-isotropic kernel elongated in the direction of vessel course over ground might be employed.

Oil spill reports

Spaceborne and airborne image sensors are often a first way to detect oil spills, capable to reach very high sensitivity; nevertheless this might come at the cost of a reduced specificity; therefore sometimes a great number of spots are identified as possible spills but with a very low confidence. The intrinsic value of such low confidence detections is generally poor, but our cumulative risk assessment method can take advantages of this information by using them as a further ingredient in the computation of risk. We assume that each oil spill report s provides a two-dimensional region R_s representing the area covered by the pollutant, a degree of confidence d_s, and a timestamp t_s representing detection time. Let χ_s be the characteristic function of the region R_s. We let the oil spill report-related risk R_{sp}:

$$\mathbf{R_{sp}(q, t)= \textstyle\sum_s w_s \cdot (\Gamma * \chi_s) (q) \cdot \exp(-\lambda|t-t_s|)} \tag{2}$$

where the sum runs over all oil spill reports, w_s is a weight proportional to the confidence d_s and Γ is a convolution kernel. Notice that the convolution $\Gamma * \chi_s$ represents the original region R_s smeared by the convolution kernel Γ.

The kernel Γ can be designed so as to optimally control the influence area of the report. The last exponential in the equation above controls the time validity of the report. The validity of the report is maximal for $t = t_s$ (i.e. when the report has just been issued), while for $t >> t_s$ (i.e. when the report becomes obsolete) the contribution becomes negligible and it is omitted in practice.

In situ observations and volunteer reports

The observation collected by the sensors scattered in the area of interests (e.g. static buoys and AUVs) as well as the information provided by volunteers can be inserted in the risk assessment in a way similar to the oil spill reports just discussed. The only difference is represented by the fact that a report s now refers to a specific point p_s and not to a two-dimensional region. However, notice that equation above works also when χ_s is the characteristic function of a point. So we may define the in situ observation-related risk as:

$$\mathbf{R_{situ}(q, t)= \sum_s w_s \cdot (\Gamma*\chi_s)(q) \cdot exp(-\lambda|t-t_s|)} \qquad \textbf{(3)}$$

where the sum runs over all in situ observations s, w_s is the weight of the observation and Γ is again a convolution kernel.

Local monitoring coverage

It has been judged important to evaluate the quality of monitoring and to integrate this information in risk assessment. Assuming that either areas with a good level of monitoring are less prone to the occurrence of accidents (since monitoring acts a deterrent) and that any actual occurrence can be promptly mitigated, it follows that the quality of monitoring reduces risk in the area. For estimating the quality of monitoring coverage, we assume that each monitoring resource m available on the field in position p_m has an effect in the nearby area with a strength that diminishes with distance. We define the quality of monitoring $Q_{mon}(q, t)$ at point q as:

$$\mathbf{Q_{mon}(q, t)= \sum_m w_m \cdot K(p_m, q)} \qquad \textbf{(4)}$$

where the sum runs over all the monitoring resources m which are operational in the time window $[t-\tau, t]$ where τ is a configurable parameter and w_m is a weight associated to m depending on the characteristics of the monitoring resource (autonomy, mitigation power,…). K is a convolution kernel such as a Gaussian kernel.

Risk assessment and multi-scale visualization

The overall risk assessment is obtained by composing the various risk terms and the monitoring quality, namely we define the risk $R(q,t)$ in point q at time t as:

$$\mathbf{R(q, t) = \alpha_{tr} R_{tr}(q, t) + \alpha_{sp} R_{sp} (q, t) + \alpha_{situ} R_{situ}(q, t) - \alpha_{mon} Q_{mon}(q, t)} \qquad \textbf{(5)}$$

where α_{tr}, α_{sp}, α_{situ} *and* α_{mon} are positive coefficients determined heuristically.

The function $R(q, t)$ can be plotted as a thematic map of risk. Its definition allows the point wise evaluation of the function R. However, to make visualization more immediate and to enhance local areas with a high level of risk at a certain scale, the region of interest has been divided by means of grids having different steps. In particular, we used three nested grids; to each block in the grid a single value of risk is associated. In this way, by visualizing the coarsest grid, it is possible to appreciate the areas that demands for more attention since they are denoted by an incremented risk. Then, it is possible to focus on such areas by visualizing the grids at a finer scale.

Proactive services for marine monitoring

A collection of services has been designed for non-stop continuous monitoring of the area of interest. The main focus has been on the optimal dynamic management of monitoring resources and on the provision of proactive services for user notification.

Essentially each service is implemented by an intelligent software agent. Agents work in autonomy and are independently reconfigurable to a large extent. Each of them has a number of probes for fetching data from the MIS and a set of preconfigured actions. It features an inner logic which represents the workflow that it is committed to carry out. Each step in the workflow is represented as a condition-action rule. The workflow might include the acquisition of further data or the triggering of external computational methods (e.g. for running simulation or assessing risk again). Agents activate their probes at regular interval of times (e.g. they poll data from a repository) or they are triggered on demand (e.g. by other agents or upon reception of special requests).

Following this framework, several services have been implemented. In particular, a simple example is given by the service for resource management which is in charge of controlling adaptively the sampling frequency of the in situ resources. Indeed, buoys and AUVs are battery powered and have therefore relevant energy constraints, which should be taken into account for deciding sensor sampling rate and periods for data transfer via radio. To this end, the service checks the overall risk status around the resource as given by the risk map and its trends as well as the status of batteries and energy harvesting system (if present, e.g. photovoltaic panels on static buoys); if the risk is low and no increment in risk has been observed, sampling rate can be reduced; similarly, rates can be increased in case of need considering trade-offs with resource autonomy. Another service for optimal resource management is related to mission planning for AUVs. In this case, based on the risk map and on the oil spill reports issued either by volunteers or by an image processing facility, the service produces a path to be followed by the AUV and a list of points where to perform water quality sampling (Colantonio et al. (2013)).

Notification services are in charge of analysing the current situation and of issuing alerts in case some anomalies are detected. In particular, oil spill reports coming from image processing facilities, volunteers' alerts and the computed risk map are monitored night and day by the services. If a report from the image processing facilities with a high confidence is found, an alert is immediately generated. In the same vein, if there are a number of volunteer's alerts which might refer to the same pollution event, an alert is generated with different levels of severity. Finally, alerts on the basis of the risk map are generated considering both the absolute value of the risk and its trend. When an alert is generated, the service takes care of contacting the most suitable authority selected automatically on the basis of a criterion of proximity. A message is composed including all the information that might be useful for understanding and evaluating the alert. In particular, the location to which the alert refers, the observations that have triggered the event and a link to an ad hoc resource of the MIS web interface are provided. Finally, the service connects thorough specific APIs with the actual dispatching interfaces (e.g. email server and GSM modem for SMS).

Field tests and results

The proposed systems has been tested in 3 field tests performed in Zakynthos, Greece (hosted by the Zakynthos Marine Park) and in Elba Island, Italy (hosted by Arcipelago Toscano National Park). The field tests were oriented to the acquisition and processing of data coming from heterogeneous resources as well as to the provision of decision support services. Cumulatively, during the tests, the MIS collected data from i) AIS receivers, ii) airborne and spaceborne image sensors and their interpretative reports regarding both oil spills and vessel detection, iii) AUVs, iv) static ad drifting buoys, v) e-Nose mounted on board buoys and AUVs, vi) volunteer alerts and vii) handheld spectroradiometer.

Tests included the acquisition of true data for verifying storage capabilities and near-real time functionalities. With a small amount of work for fixing interoperability issues, no problems were found for data integration. Stress tests using dummy data have also been performed for understanding the limits of the platform. On this basis, it can be judged that the system is adequate for managing regional data; in any case the system might be scaled to arbitrarily wide areas. Support for multiple areas is already included and operational. Besides true data, fake data were also injected into the MIS to produce artificial perturbations and thus creating interesting anomalies to be managed by the proactive services. The methods for real-time risk assessment were run automatically at regular time intervals to produce risk maps. The maps were visualized by experienced users (an example of the appearance of the map at the coarse scale is given in Figure 2) as well as stored into a database. By visual inspection, the users found the map to convey meaningful and significant information and regarded it as a useful tool to better focus the attention on the areas that deserve a more accurate monitoring.

The proactive services were asked to poll data from the databases including the computed risk maps. On the basis of polled data and of the logic used by the services, suggestions for resource management and alert notifications were issued. Among various tests, four volunteers have been asked to report (by using either a specially-designed device or a custom app on their GPS-equipped smartphone a (fake) oil spill. The computed risk map changed consistently after receiving the volunteer reports (see Figure 2). In the same vein, a simulated packet was injected into the MIS for artificially reproducing the case in which the e-Nose perceives the presence of hydrocarbons in the nearby area. As shown in Figure 3, such an event triggers a list of actions; in particular the risk map is updated and the decision support services issue a notification to the authorities competent for the area.

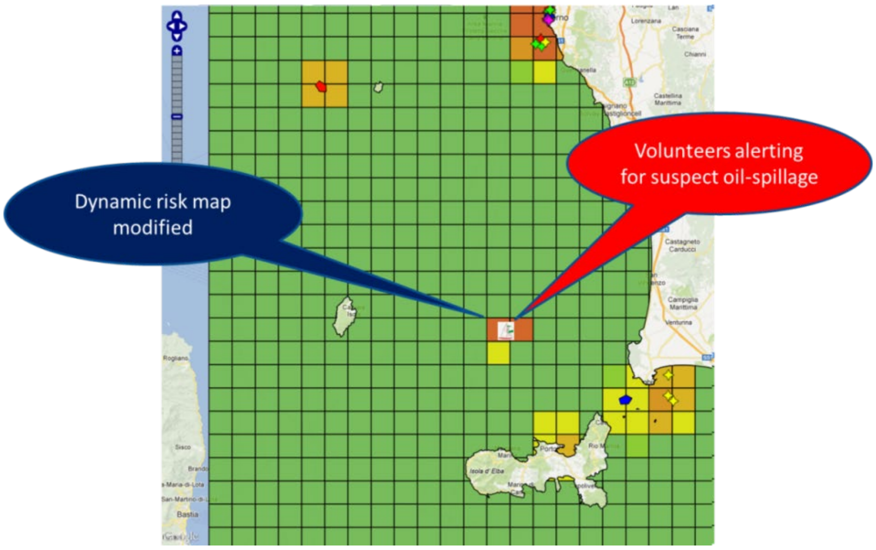


Fig. 2: MIS interface showing dynamic risk map modification due to a volunteer alerting.

Argo Alerter
+393488998701
19/11/2012 Lun
An alert, with high severity, has been raised in your area of interest. Please check your email.

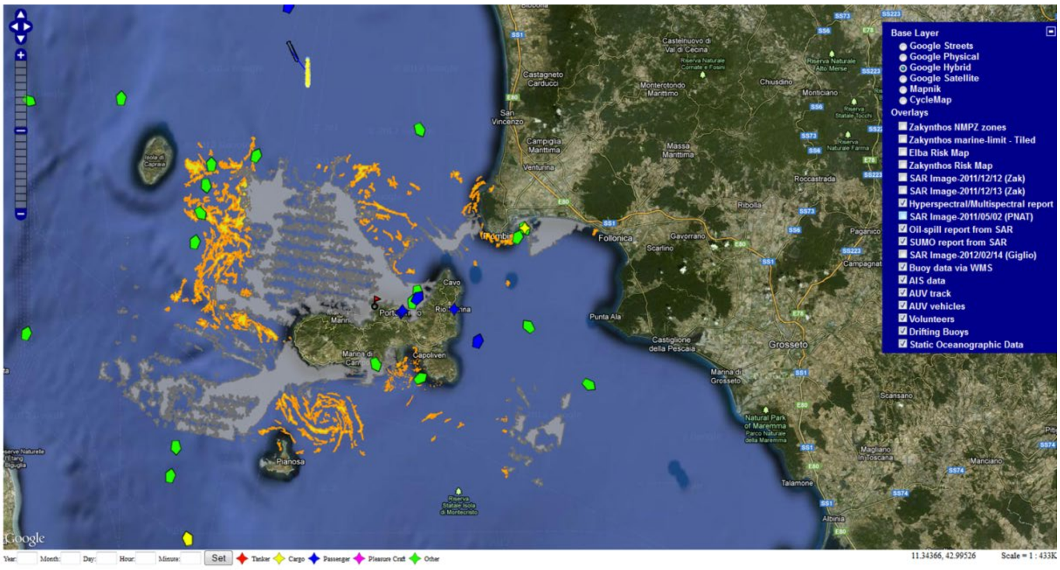
Buoy1

- *battery*: 11.8235
- *temperature*: 15.4
- *hydrocarbon*:
- *humidity*: 9.2
- *Wind speed*: 0.0
- *Dew point*: -17.1386
- *General acceleration*: 9.8
- *Last data acquired on*: Nov 19, 2012 10:21:48 PM
- *rain*: 0.0
- *blackmean*: 19
- *blackmax*: 30
- *bronzemean*: 8
- *bronzemax*: 35
- *silvermean*: 40
- *silvermax*: 110
- *enosehumiditymean*: 47
- *enosehumiditymax*: 49

Show buoys historic values *(coming soon)*

Fig. 3: MIS interface during test field: above, the generating event from an eNose sniffing transmitted to the MIS, and the DSS generating a preliminary alert; below, the modification of the dynamic risk map along with the display of the detailed event occurred.

The notification is sent both via SMS (where few details are given) and via e-mail where the full description of the event is provided. Indeed a specific link is provided to the web interface of the MIS. On such interface, the user can explore the map and visualize informative popups containing all the measurement performed by the buoy mounting the e-Nose. The interface allows also to cross-correlate the reports with the maritime traffic as well as the last SAR images report (see Figure 4).

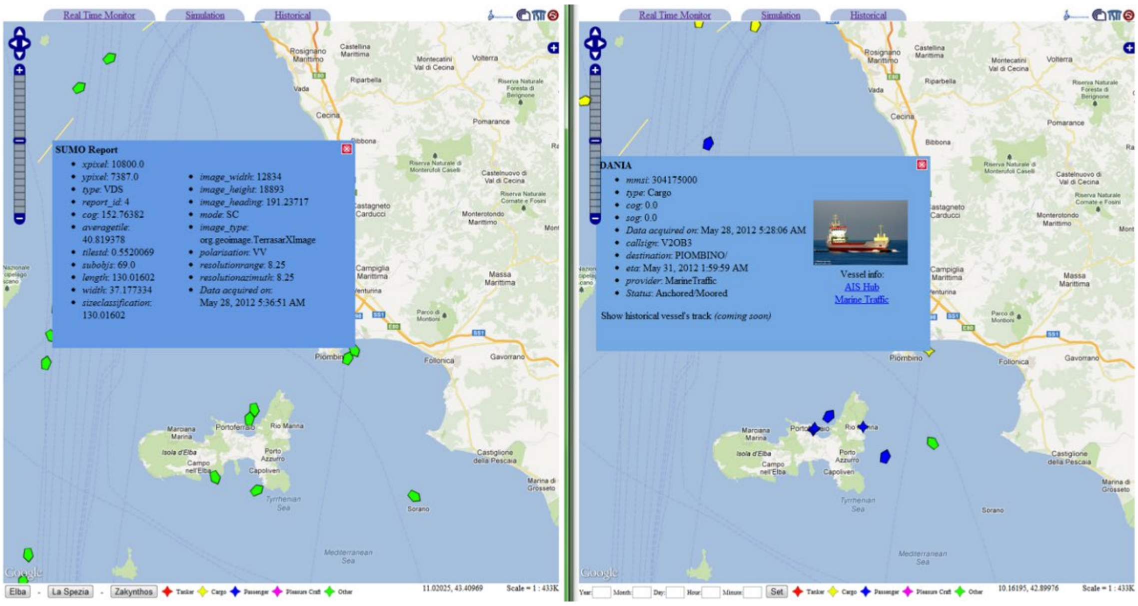


Base Layer
- ○ Google Streets
- ○ Google Physical
- ● Google Hybrid
- ○ Google Satellite
- ○ Mapnik
- ○ CycleMap

Overlays
- ☐ Zakynthos NMPZ zones
- ☐ Zakynthos marine-limit - Tiled
- ☐ Elba Risk Map
- ☐ Zakynthos Risk Map
- ☐ SAR Image-2011/12/12 (Zak)
- ☐ SAR Image-2011/12/13 (Zak)
- ☑ Hyperspectral/Multispectral report
- ☐ SAR Image-2011/05/02 (PNAT)
- ☑ Oil-spill report from SAR
- ☑ SUMO report from SAR
- ☐ SAR Image-2012/02/14 (Giglio)
- ☑ Buoy data via WMS
- ☑ AIS data
- ☑ AUV track
- ☑ AUV vehicles
- ☑ Volunteers
- ☑ Drifting Buoys
- ☑ Static Oceanographic Data

Fig. 4: Different MIS interface showing detected oil-spill layer from SAR images processing, having different levels of probability.

As a further result, a cross-correlation was performed among different data sources in order to prove the efficiency and reliability of the different available information. As an example in the following Figure 5, a comparison of the acquisition from AIS source (on the right) and SAR image classification with detected vessels (left) is shown. In more detail, the geo-referenced report from SAR classification has been temporally registered with the correspondent AIS data, and overlapping data on the respective layers compared for correlation. Among the different information that can be extracted and compared, the most useful is the size of the vessels, considering also that not all the vessels are obliged to issue AIS signal, whereas larger ships like tankers are obliged. Moreover, one have to take account of a confidence and error interval due to lack of synchronization between the various heterogeneous data, which can also lead to a possible geographic misplacement. The sample reported in Figure 5, shows a ship whose classification is correct and positively correlated to the SAR detection, moreover the size class (130 meters detected versus 100 meters actual), is within an acceptable range. Regarding the amount of ships detected through the SAR classification, that are many more than the detected through AIS data, this is due mainly to the fact that only larger ships are obliged to send AIS signal.



SUMO Report

- *xpixel*: 10800.0
- *ypixel*: 7387.0
- *type*: VDS
- *report_id*: 4
- *cog*: 152.76382
- *averagetile*: 40.819378
- *tilestd*: 0.5520069
- *subobjs*: 69.0
- *length*: 130.01602
- *width*: 37.177334
- *sizeclassification*: 130.01602
- *image_width*: 12834
- *image_height*: 18893
- *image_heading*: 191.23717
- *mode*: SC
- *image_type*: org.geoimage.TerrasarXImage
- *polarisation*: VV
- *resolutionrange*: 8.25
- *resolutionazimuth*: 8.25
- *Data acquired on*: May 28, 2012 5:36:51 AM

DANIA

- *mmsi*: 304175000
- *type*: Cargo
- *cog*: 0.0
- *sog*: 0.0
- *Data acquired on*: May 28, 2012 5:28:06 AM
- *callsign*: V2OB3
- *destination*: PIOMBINO/
- *eta*: May 31, 2012 1:59:59 AM
- *provider*: MarineTraffic
- *Status*: Anchored/Moored

Show historical vessel's track *(coming soon)*

Fig. 5: Cross-correlation shown between AIS and SAR classification data acquired and registered.

Conclusions

This paper presented an integrated and interoperable system based on advanced sensing capabilities from a variety of electronic sensors along with geo-positioning tools, suitable for local authorities and stakeholders in the monitoring and management of sea and coastal oil pollutions. The Marine Information System implemented integrates various environmental data acquired both in situ and remotely, and it is enhanced with various environmental decision support services, aiming at an automatic screening of the real-time situation, a quantitative representation of the risk factors, and most notably a proactive notification of events and suggestion useful in the intervention chain for the management of pollution situations. The architecture of the implemented MIS has been presented, followed by specifications on the methods used for real-time risk estimation and the services realized for environmental monitoring.

Taking into account that the proposed and implemented MIS was for the purpose of a research project, therefore bound to be a proof of feasibility, and not a continuously operative system, the known limits and constraints of such an architecture rely on the possible lack of availability of data.

Finally, demonstration of the proposed system has been shown during extensive test exercises held at the National Marine Park of Zakynthos and at National Park of Tuscany Archipelago in the framework of FP7 Project Argomarine.

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