International Environmental Modelling and Software Society (iEMSs)
2012 International Congress on Environmental Modelling and Software
Managing Resources of a Limited Planet, Sixth Biennial Meeting, Leipzig, Germany
R. Seppelt, A.A. Voinov, S. Lange, D. Bankamp (Eds.)
http://www.iemss.org/society/index.php/iemss-2012-proceedings

Proactive Environmental Systems: the Next Generation of Environmental Monitoring

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Abstract: In this article we envision factors and trends that shape the next generation of environmental monitoring systems. One key factor in this respect is the combined effect of end-user needs and the general development of IT services and their availability. Currently, an environmental (monitoring) system is assumed to be reactive. It delivers measurement data and computational results only if the user explicitly asks for it either by query or subscription. There is a temptation to automate this by simply pushing data to end-users. This, however, leads easily to an “advertisement strategy”, where data is pushed to end-users regardless of users’ needs. Under this strategy, the mere amount of received data obfuscates the individual messages; any “automatic” service, regardless of its fitness, overruns a system that requires the user’s initiative. The foreseeable problem is that, unless there is no overall management, each new environmental service is going to compete for end-users’ attention and, thus, inadvertently hinder the use of existing services. As the main contribution we investigate the nature of proactive environmental systems, and how they should be designed to avoid the aforementioned problem. We also discuss how semantics, participatory sensing, uncertainty management, and situational awareness link to proactive environmental systems. We illustrate our proposals with some real-life examples.

***Keywords**:* Environmental monitoring; Participatory sensing; Uncertainty management; Software agents.

1 INTRODUCTION

The role of environmental measurement and monitoring systems is steadily increasing in our everyday lives. Consequently, as pointed out by Messer et. al [2006], “High-resolution, continuous, accurate monitoring of the environment is of great importance for many applications— from weather forecasting to pollution regulation.” However, despite this synergy between the measured phenomena, each system is considered as a separate entity, having Web services of its own. This is in part because environmental monitoring systems are still undergoing significant development.

As the number of environmental monitoring systems increases, so does the number of services and possibilities. The increasing range of algorithms, services and processing functions with Web interfaces vastly expands these possibilities, by opening opportunities for the chaining and orchestration of many data and analysis components. Therein, however, lies the problem of reactive systems: interoperability, or rather, the lack of it. As more systems with comparable scope and capabilities become available, it becomes harder for the end-user to identify the “best” system for a specific purpose. This is a significant problem, in particular, if one has to combine services to obtain the required results. The problem becomes even worse if some of the data sources lack semantics. Ideally, a user may apply advanced computational methods such as ontology learning, described by Stocker et al. [2011] and uncertainty management, described by Williams et al. [2011]. Uncertainty management becomes especially critical if some of the combined services involve participatory sensing with data of heterogeneous quality, as described for instance by Karatzas [2011].

Participatory sensing is a significant step towards bridging the gap between systems and their end-users. Still, it does not remove the heart of the problem. The environmental monitoring systems are built as separate, reactive, entities. The systems may provide both pull and push services through query and subscription interfaces, respectively; however, the initiative must always come from the end-user. In this respect, no matter how high the quality of available services, if the end-user is not aware of them, and has thus not subscribed to them, those services are of no use.

Some services, specifically advertisement services, approach the problem of reaching the end-user by contacting any known or potential customer. These services are pushing data to end-users regardless of users’ needs, hoping to gain users’ attention. This strategy, however, does not fit well to environmental systems and services, because then the sheer quantity of received data may obfuscate the individual messages. Consequently, any uncontrolled data-push service, regardless of its fitness, will overload a system that actually requires the user’s involvement. The foreseeable problem here is that each new environmental service is going to compete for the end-user’s attention and thus, inadvertently hinder the use of existing services.

In this article, we consider what it means for an environmental system to be proactive. In short, the major difference between a proactive environmental system and an ordinary reactive environmental system is that a proactive environmental system has the initiative. In particular, a proactive environmental system contacts the end-user even about a topic that the end-user is not aware of, but which the system believes is of importance to the end-user. We explain and argue how proactiveness supports interoperability and solves the problem of reaching the end-user. We also discuss what advantages a proactive environmental system has, with reference to three specific use cases.

There are many ways to implement proactiveness, whereby we focus in this article on describing the key features of a proactive environmental system that sets it apart from reactive systems. In this respect, a proactive environmental system needs to embody some situational awareness, or situation awareness as described for instance by Endsley [1995]. It has to be able to learn from end-users’ behaviors, including participatory sensing, and to predict the needs of individual end-users in order to take the initiative. A proactive environmental system has to also include uncertainty management and propagation in order to combine sources of information reliably in such a way that it can also convey the uncertainty of the outputs to the end-user.

To illustrate the advantages of proactiveness, we present three real-life use scenarios and explain how uncertainty management, participatory sensing, and situational awareness manifest in those scenarios. We then discuss how a proactive system would solve the underlying problems in the scenarios.

The remaining of this article is organized as follows. In Section 2, we define the concepts: environmental information systems, participatory sensing, uncertainty management, and situational awareness. Using these concepts, in Section 3, we describe what a proactive environmental system is and what its key features are. In

Section 4, we present three scenarios and explain how uncertainty management, participatory sensing, and situational awareness manifest in the scenarios. In Section 5, based on the three scenarios, we discuss how a proactive systems could solve the underlying problems related to the scenarios. Finally, in Section 6, follows the conclusion.

2 ENVIRONMENTAL SYSTEMS AND THEIR ASPECTS OF INTEREST

In order to discuss proactive environmental systems, we briefly define what we mean by an environmental information system. We then define the systems' aspects that are of interest when considering proactiveness.

Environmental Information Systems. Athanasiadis et al. [2004] define environmental information systems (EIS) as a class of systems dedicated to environmental data and data processing. More specifically, such systems are used for instance for environmental monitoring, reporting, planning, simulation, modelling, and decision making. Environmental information systems also may provide data capture and measurement services as well as data storage and access services. Examples of modelling EIS (implemented as Web Processing Services) include the INTAMAP interpolation Web service and the eHabitat application which predicts natural habitat availability under current and future climate scenarios. Other examples of EIS include ToMoVaKe platform which is an outdoor sensor network for safety and security related monitoring applications; AsTEKa which is an indoor air quality and energy efficiency measurement and monitoring system; EnviObserver which is a participatory sensing platform for monitoring environmental changes.

Uncertainty management. All measurements are subject to uncertainty, with component contributions from sources such as instrument quality and calibration, operator error, imprecision in reported measurement location and representativity of natural variation. Thus the sensors underlying environmental monitoring have an inherent unreliability which, ideally, should be quantified, communicated to the user and, where possible, reduced using techniques such as bias learning and correction. In addition, there are numerous stages in the transformation of data into useful information: for example, interpolation, cluster analysis, predictive modelling, outlier removal and the comparison of spatial patterns to simulated or hypothesized 'nulls' to identify significant processes. Each of these manipulations can further propagate uncertainty in the outputs, as discussed by Heuvelink [1998], but without well-quantified uncertainty on inputs and models, it is difficult to assess the final impact on the reliability of the information produced. Techniques for uncertainty and sensitivity analysis are being increasingly shared in the modelling community, see work done by Mattot et al. [2009] and Bastin et al. [2012], but in an interoperable environment it is essential that some standard approach is used to exchange the uncertainty information between services in multiple disciplines and application domains, as discussed by Williams et al. [2011].

Participatory Sensing. In participatory sensing, as presented by Burke et al. [2006], mobile devices and their users form a mobile sensor network. In the network, both users and devices interact, enabling gathering, sharing, and analysis of local information. Consequently, participatory sensing supports creation of services, for instance, for quality of life as discussed by Karatzas [2011]. As participatory sensing supports gathering of subjective experiences, for instance, regarding air quality, it provides a form of interpreted information that, with proper uncertainty management, supports personalization of measurement data. In particular, it supports development of models for personalized interpretation of forecast data for risk groups. Thus, participatory sensing is a central complementary tool for enhanced situational awareness.

Situational awareness. There are many models for situational awareness. In this article, however, we use the seminal model by Endsley [1995]. In short, situational awareness consists of three cognitive processes; perception, comprehension, and projection of future status. Here, perception comprises both sensing and the ability to distinguish features. Comprehension refers then to the process of understanding the implications and significance of a perceived setting with its features. Lastly, projection of future status essentially captures actor's knowledge and experience on how the comprehended state evolves over time. It should be noted that in this model, similarly to other situational awareness models, there is a strong emphasis on differences between individuals. Hence, a situational awareness model ought to be used to analyze an information system, to detect shortcomings and factors that neglect to take into account the differences between users and their cognitive processes.

3 PROACTIVE ENVIRONMENTAL SYSTEMS

The central difference between an ordinary environmental system and a proactive environmental system is that the proactive environmental system takes initiative. Rather than waiting for the end-user's query or request, a proactive environmental system contacts the end-user even about a topic that the end-user is not aware of, but which the system believes is of importance to the end-user.

A proactive environmental system acts, thus, as a coordinator between a heterogeneous set of systems and the end-user. In order to do this efficiently and reliably, it must embody certain aspects: situational awareness, uncertainty management, support for interoperability, and participatory sensing. We shall now discuss briefly how each of these aspects contributes to proactiveness.

Situational awareness is needed by a proactive environmental system to provide timely and appropriate communication. To embody situational awareness, a proactive environmental system has to be able to perceive the needs of the end-user and comprehend those needs to an extent that it can contact external resources and request missing data if needed. It also needs to be able to project future actions of the end-user, to have some measure for confidence and importance. In addition to this, a proactive system should also enhance end-user's situational awareness. In other words, delivered services must improve end-user's perception and comprehension about the state of affairs. Furthermore, a proactive system must support the end-user in seeing effects of future actions. To capture all this, a necessary requirement for the system is to be able to learn from the behaviours of all end-users, and to be able to set obtained patterns in a proper context. The context could be encapsulated, for instance, by ontologies, and refined by ontology learning, as discussed by Stocker et al. [2011]. The projection of future actions requires additional profiling of end-user actions and communications. Clearly, there is no single learning algorithm to capture all this; rather, a diverse set of unsupervised learning methods and reinforcement learning has to be used.

An integral feature of a proactive environmental system is that it provides critical information to an end-user reliably. Because of this, uncertainty management is needed. The end-user has to at least know if the information can be trusted and to what degree. The system should also be able to argue both the relevance and the uncertainty factors related to the information. Ideally, however, the proactive system must itself comprehend what constitutes relevance and reliability, to transform obtained data into such form that it brings additional value to the end-user. Such comprehension is not possible in an automated system without well- defined information models which encapsulate clear definitions of the elements of metadata and of data quality. The quality information model proposed by the EU-funded GeoViQua project (Yang et al, in review) proposes a means by which qualitative, numerical and hierarchical quality information can be encoded and transformed with reference to standardised shared dictionaries such as UncertML, facilitating this semantic understanding of the many aspects of uncertainty. Such methods also help in constructing belief structures that somehow model future needs to individual end-users.

To avoid congestion by communication, a proactive environmental system has to be able to use and benefit from external resources, including data sources and computational services. This, however, brings in the need for interoperability. The ability to query data from a known, external source based on a specific need is simply not sufficient. The system must have the ability to recognize and start using autonomously new external sources. This requires machine interpretable metadata from external sources, and semantic deduction and comprehension of how metadata relates to an ontology used by the proactive environmental system. Note that the interoperability of a proactive environmental system must not be limited to interaction between information systems. The proactive environmental system must also know what is the best and preferred means to contact a human end-user at any given time. The communication media may, thus, for instance include specific application interfaces, emailing, and SMS messaging.

By monitoring communication taking place in a participatory sensing network, a proactive environmental system can actively learn and profile users and their behaviour. By learning patterns of behaviour, the proactive environmental system could start predicting future actions of end-users. This information could be used, for instance, for validating learned belief structures and learned models for situational awareness. Note that the proactive environmental system should also be a participant in a participatory sensing network. This would allow it to initiate communication and to validate observations by end-users.

It is clear that there are many ways to implement proactiveness, and a very heterogeneous set of algorithms is needed to implement all the features discussed above. One possible overall framework for implementing a proactive environmental system is an agent framework, such as JADE by Bellifemine et al. [1999] used for instance by Athanasiadis et al. [2004], or some other agent framework based on specifications by FIPA [2004] similarly to work done by Purvis et al. [2003]. For JADE, there exist belief-desire-intention reasoning extensions, such as Jadex by Pokahr et al. [2005], which could support implementation of goal-directedness and rationality using planning and collaborative decision making. These features are central when considering implementation of models for situational awareness, collaborative uncertainty management, and interaction with participatory sensing.

4 SCENARIOS OF INTEREST

Next we present briefly three real-life scenarios, where the success of communication has significant impact on the safety of systems and human beings. For each scenario, we point out features that relate to proactive environmental systems. It should be noted that, although the scenarios are from the field of safety and security, proactive environmental system apply to everyday life examples, too.

4.1 Scenario 1: Volcanic Ash Disrupts the Aviation Industry in Europe

In the first scenario, due to volcanic activity, volcanic ash is dispersed into the atmosphere, blocking the majority of airlines between European countries. This affects thousands of people in an hour causing significant financial losses.

In this scenario, uncertainty management is crucial, when trying to forecast the development of the dispersion of volcanic ash. The more reliable the measurements and models used in the forecast, the smaller the risks and risk margins become. Accurate and reliable modelling of dispersion supports narrowing of flight restrictions, which in turn limits financial losses. Full presentation of rich uncertainty information such as detailed maps of exceedance probabilities allows the user to set their own threshold of acceptable risk for errors of commission and omission, and to weight these according to context-specific costs.

Participatory sensing during flights helps validating dispersion modelling results, and provides feedback for uncertainty estimations and management. Participatory sensing among travellers helps to coordinate options and possibilities for alternative travelling routes. Without coordination, travellers may independently decide to use the same alternative routes causing congestion on active travelling routes.

From travellers' point of the view, situational awareness is needed to see the global scale of the event, in order to consider also other alternatives, such as temporary accommodation over the worst period of the event. Similarly, travelling agencies need a shared situational awareness of the intentions of travellers to coordinate possible alternative travelling routes.

4.2 Scenario 2: Chemical Transportation Incident Causing Evacuation

In the second scenario, chemicals leaking from transportation containers cause immediate danger to nearby population. Because of this potentially affected people are evacuated and incident mitigation is started.

In this scenario uncertainty management is central. The evaluation of the potential risk for the nearby population is based on the toxicity of the chemicals and the amount of leaked chemicals. Also, for the evaluation, an estimate of the leaking speed needs to be determined. All these factors are measured or estimated with some intrinsic uncertainty. During the mitigation the measurements and estimations become more accurate, supporting risk reassessment based on updated prior knowledge and remaining uncertainties.

Using participatory sensing, people outside the evacuation area can report deviations, anomalies, or problems that may help in further assessing the contamination area and potential need for enlarging the evacuation area. Participatory sensing could also alert transporters of other chemicals to avoid the incident region and plan the routes safely in advance.

The rescue workers need a shared situational awareness to focus their work during the incident mitigation. In particular, if the estimates are unreliable, shared situational awareness helps in detecting if planned actions fit the scale of the incident.

4.3 Scenario 3: Gas Leak in a Shopping Centre

In the third scenario, there is a gas leak in a shopping centre during a warm summer day. Because there is a single emission point in the shopping centre, the concentration remains low in overall. However, the concentration is high enough to cause, for instance, difficulties in breathing for some customers.

In this scenario, participatory sensing is central. If individual customers report about problems and difficulties, an overall situational awareness of multiple incidents can be formed. Furthermore, with geo-location, a map of incidents and observations can be drawn, to indicate if the incidents are limited to a certain area of the shopping centre. This helps in detecting the cause of the problems.

It should be noted when some individual people in a shopping centre have minor health issues, a gas leak is hardly considered as a primary reason. Typically, in a warm summer day, weather conditions and lack of fluids are considered as the first choice. In this case, participatory sensing could indicate to officials and authorities that there are multiple incidents, and they occur in a limited area. This would help significantly in determining a common cause for the reported incidents.

Reliability and consistency analysis of reported observations helps in distilling salient observations and their potential origin from non-related observations.

5 DISCUSSION

When considering the three scenarios presented above, a proactive environmental system could significantly improve safety and efficiency. In particular, in Scenario 1, use of a proactive environmental system would improve communication efficiency, provide early awareness, reduce communication congestion, and provide a coordinated awareness to intentions and plans of travellers. Similarly, in Scenario 2, use of a proactive environmental system would improve notification and evacuation efficiency, help detecting differences between estimated and real contamination area through participatory sensing, and improve mitigation by requesting rerouting of transportation around contamination area. Lastly, in Scenario 3, use of a proactive environmental system would help detecting an incident pattern that could otherwise go unnoticed.

Although there are clear advantages of using a proactive environmental system, the development of one is not straight forward. For instance, integration of many information systems requires significant effort and updates in those systems would cause updates also in the proactive system. Integration in itself is already a challenge, as many information systems are not built for interoperability. They may lack, for instance, metadata which can be interpreted across distinct disciplinary fields and rigorous application interfaces. This means that the believed semantics of data may well be different from what it actually is, causing contradictions in automatic deduction processes. Another limiting factor is jurisdiction, as laws in individual countries have differences; a service that is legal in one country may well be illegal in another. Also, as a proactive environmental system needs to profile its users, there is the issue of privacy. More specifically, it is not clear how to collect all the data required for profiling while ensuring privacy.

Also, as a proactive environmental system is to some degree a centralized system, it has significant requirements for reliability and robustness. The system should tolerate disconnections and even failures in the integrated system without having a significantly degraded operability. Also, from end-users' point of the view, the system should behave predictably, and it should be trustworthy. In particular, as mentioned above, privacy of the end-user should be guaranteed.

6 CONCLUSION

In this article, as the main contribution, we proposed the use of proactive environmental systems. For this purpose, we defined proactiveness and explained how participatory sensing, uncertainty management, and situational awareness link to it. We also presented three real-life scenarios as examples and, with the scenarios, explained how proactive environmental systems could improve quality of life, efficiency and safety of citizens.

The research on proactive environmental systems is at its very early stages. There are many juristic, theoretical and technological challenges that need to be solved. However, when considering recent advances in software engineering and cloud computing, the software architectural components, such as software agent technology, do already exist for initial prototyping of systems components.

As for the future work, the first steps could be experimenting with integration of environmental Web services through a software agent platform. The platform could then be extended with Web service metadata and agents capable of simple artificial deduction. Such an extended platform could then be used as a basis for implementing a proactive environmental system for the presented case studies.

ACKNOWLEDGEMENTS

Rönkkö, Kolehmainen and Stocker wish to thank European Regional Development Fund and the Finnish Funding Agency for Technology and Innovation (TEKES) for funding part of this research (funding decision number 70038/11).

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