Computerized System to Enhance Situation Awareness: Key Challenges Associated with the Design, Evaluation, and Extension of a Prototype

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ABSTRACT

Successful decision making and task execution in emergency management require appropriate levels of situation awareness (SA). This paper proposes an ontology-based model for the design of a computer-based system, Situation Aware Vigilant Emergency Reasoner (SAVER) that supports the individual, shared and team SA of managers in emergency situations. SAVER is evaluated in simulated experiments that demonstrate the improvements in SA performance. The paper provides a complete description of the SAVER design, implementation, evaluation and its proposed extension from a proof-of-concept to a production environment.

Keywords

Tsunami, Situation Awareness, Team Situation Awareness, Shared Situation Awareness, SAVER

INTRODUCTION

Large-scale emergencies such as tsunamis or volcanic eruptions are managed by several teams, e.g. emergency managers, military, police, fire services, healthcare professionals, etc. Close coordination within and between teams is essential since the failure of a single link can risk the whole operation, for example, the mass evacuation of a city or region. Decision-making in such emergencies is necessarily complex as the situations are dynamic, unfolding rapidly, and invariably stressful.

Computerized decision support systems can facilitate and improve coordination and decision making by presenting, structuring, processing, and interpreting huge amounts of information in a short space of time. However, the power of such systems is enhanced even further if they are designed to improve the situation awareness (SA) of individual managers, their shared situation awareness (SSA), and team situation awareness (TSA). The goal is to ensure that team members have a comprehensive understanding of the situation not just for their individual roles but also of the roles of their colleagues.

This paper described an information system dubbed Situation Aware Vigilant Emergency Reasoner (SAVER) based on SSA and TSA design principles. Some of the individual details of SAVER have been explained elsewhere (Javed and Norris, 2011; Javed, Norris and Johnston, 2012) and this paper describes the full design, development, implementation, and evaluation of the system and develops a further aspect of SAVER design related to the use of ontology for contextual information retrieval. The paper also suggests how the prototype can be developed into a production system.

ROLE OF SA, SSA AND TSA IN EMERGENCY MANAGEMENT

The process of understanding a prevailing situation to achieve a set of goals is called situation assessment and this process results in a product named situation awareness (SA). SA is the degree to which each individual understands the situation. Several studies have described SA as a crucial factor for better decision-making (Bryant, 2002; Klein, 2000) and the seminal work by Endsley and others has shown its close relationship with emergency decision making during time critical and complex situations (Endsley, 1995; Smith and Hancock, 1995).

As indicated, emergency managers usually work in teams and to function effectively, each team member must share a common understanding of a situation so that they can coordinate their decision making and actions. Different assessments of the situation can lead to uncoordinated or even counter-predictive behavior. The degree to which team members possess the same understanding of a situation is defined as shared situation awareness (SSA) as it refers to the overlap between members' individual SA.

However, this overlap in itself may not be sufficient to achieve the required response to an emergency. Each team member contributes role-based sub-goals to the overall goal and each participant must possess the SA needed to discharge their role (responsibilities) in relation to others' activities. The degree to which every team member possesses this SA is known as team situation awareness (TSA). TSA thus depends upon high levels of both individual SA and shared SA amongst members (Endsley and Jones, 2001). With low SA, individual members have a poor understanding of the situation, and with low SSA they tend to focus only on their own roles ignoring their team contribution and the actions of their colleagues. These conditions result not only in the repetition of various activities but also delay or curtail tasks leading potentially to the failure of the whole mission due to the inability of team members to integrate their individual and shared awareness.

Some recent research to improve SA in emergency decision-making has made use of computer-based systems, e.g. (Betts, 2005; Prasanna, Yang, and King, 2009; Ferreira, Dantas, Seville, and Giovinazzi, 2009). Several studies (O'Connor, Campbell, Newon, Melton, Salas, and Wilson, 2008; Lanfranchi & Ireson, 2009; Madey, Szabo, and Barabasi, 2006; Son, Aziz, and Pena-Mora, 2007) have also explained how a system fulfilling SA requirements can maintain the required level of SA and better support such decision-making. However, these studies tend to underestimate the critical role of SSA and TSA. At the same time, very little work has been done to see how SA, SSA, or TSA can be improved. This paper describes the design and development of a prototype computer system (SAVER) to improve SA, SSA, and TSA and its evaluation for decision making and implementation during mass evacuation following a tsunami. Further information on the SAVER design and performance is available elsewhere (Javed et al., 2012).

The study was carried out in New Zealand simulating tsunamis generated by undersea earthquakes but the system and results should be transferable to other countries and emergency situations.

SAVER DESIGN AND DEVELOPMENT

In Endsley's seminal model of SA, an individual's SA requirements are defined as the dynamic information needs associated with the person's goals (Endsley, 2000; Wickens, 2008). Hence, supporting their SA will mean providing them with the information they need to make correct decisions and carry out the tasks to achieve these goals (Albers, 2004). Endsley's model differentiates three levels; perception (Level 1), comprehension (Level 2) and projection (Level 3) at which relevant information should be provided.

The information requirements of different emergency roles needed to develop and maintain the SA for various phases of mass evacuation have been gathered and reported previously (Javed, Norris, Johnston, and Doyle, 2011). These requirements are the basis of our system design. To provide specific and easily used information, SAVER considers the users' contextual parameters, i.e. their roles, responsibilities, goals and tasks and, more importantly, the information required to develop and maintain their SA to carry out these tasks. In effect, SAVER provides the right information to the right persons at the right time. This overall objective is attained by the semantic modelling of the contextual information (Chen, Finnin, and Joshi, 2004).

Acquiring Context Specific Information

Context information about the managers, their tasks, activities, and situational roles can be used to distinguish them from one another (Chen et al., 2004). Moreover, the same attributes can be used to provide the specific information they require. Hence, systems using the context information to provide services are called context-aware systems.

SAVER automates the processing of context information (roles, current objectives, tasks and location etc) and combines them with SA requirements to fulfil the contextualised SA requirements. The system also uses contextual information for adaptive user interface and adaptive content generation. Figure 1 shows how various context parameters can be used to provide specific information to the users in a personalised form.

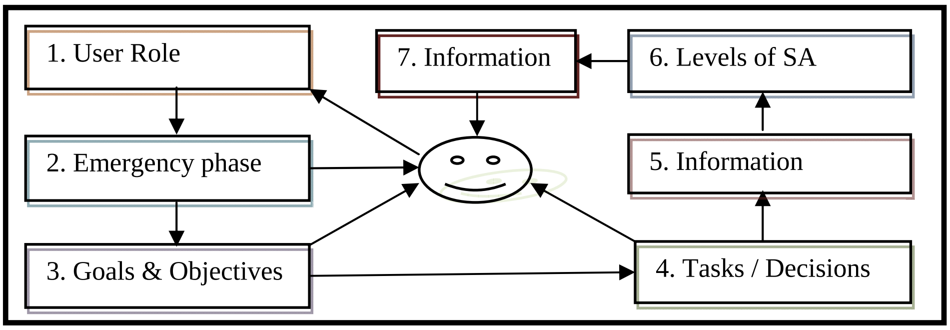

Figure 1: Selecting specific information for users using contextual information

Acquiring an accurate picture of context is a great challenge in context-aware systems. Our research uses ontology-based modelling and inferring of context information to provide personalised information to emergency managers.

Context Reasoning and Ontology-based Inference

Context reasoning is a method of processing the context information and making it usable in context-aware systems. Context reasoning also detects and resolves inconsistent information about the context. To enable automatic processing of context information it must be presented in machine processable form. Previous work (Schilit, Adams, and Want, 1994; Asthana, Cravatts, and Krzyzanowski, 1994; Dey, 2000) has presented contextual information using data structures or class objects in programming languages. However, since these languages only provide syntax representation they lack semantic representation and hence interoperability, which is considered essential for information sharing (Chen et al., 2004).

Chen et al. (2004) proposed an ontological, rule-based, logical inference architecture called CoBrA to enable context reasoning. Web ontology language (OWL) is a perfect fit for presenting context information since it is flexible enough to model context information in formal language (machine processable) and also allows rule-based inference. Another important reason for choosing an ontology-based approach for context reasoning is that our research already uses ontology-based situation modelling (Javed et al., 2012). Therefore, both situation modelling and context reasoning can have a seamless interface. One of the advantages of this approach is the flexibility for extension. For example, it would be very easy to add more dimensions of context information, e.g. types of devices (desktop computers, smart phones, personal digital assistants, computer tablets etc.), to provide personalised information according to the device features (Christopoulou and Kameas, 2005).

System Architecture of Ontology-based Contextual SA

SAVER detects the user login and provides this information to the context ontology. The reasoner checks whether there is any prevailing emergency situation from the activities log, e.g. activities performed by emergency managers from the time when an earthquake occurred to the current time, and infers the current state of the emergency situation. However, the user can also manually update the emergency phase status in SAVER. The stepwise process of an automatic emergency phase change is as follows. Each sub-class of Time has a data property *"currentStatus"* which can have a Boolean value, i.e. true or false. Only one phase can have "true" as a *currentStatus* and status can only be changed in sequence, i.e. from "pre-confirmation phase" to "tsunami confirmed decision phase" and so on. Hence, SAVER can support the SA of emergency managers by providing the personalised information required for developing the desired level of SA. Moreover, it improves SA by providing Level 2 and 3 SA information directly to update human SA (Salas, Prince, Baker, and Shrestha, 1995).

To support the common understanding of the situation, which is called TSA by Salas et al. (1995), SAVER can provide the explicit situation assessment along with the reasoning. The reasoning in the form of logical arguments can clarify any doubts in the minds of emergency managers and they can be confident that their understanding of the prevailing situation is correct and shared at both individual and team levels. Sharing of the member's SA will improve the other team members' confidence (if there is a match) or otherwise it will give them a chance to analyze the situation critically.

The semantic modeling of the situation and user context can maximize the proactive sharing of information requirements needed to develop a common understanding of the situation. The semantics can also enable

SAVER to identify and automatically share (with user consent) the information about a team member that is a required by another member.

Figure 2 shows the architecture design of SAVER using ontological contextual and situation reasoning.

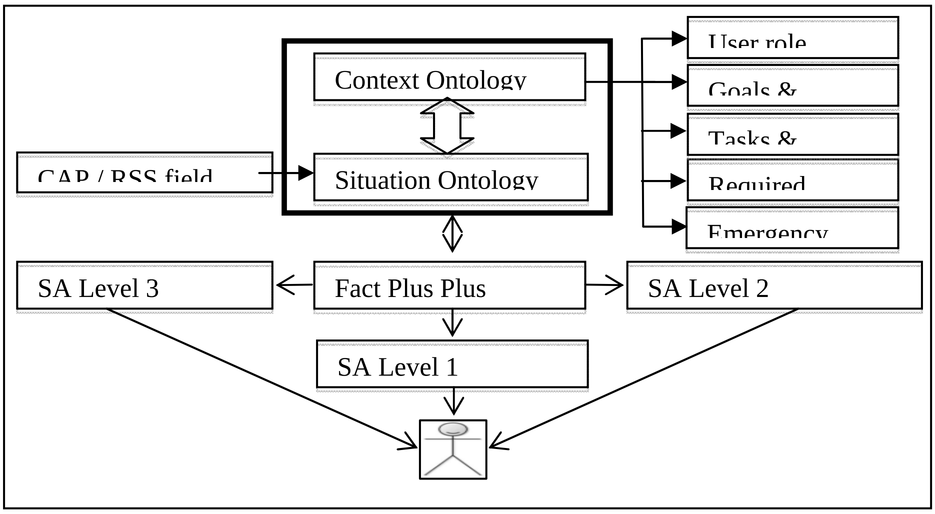

Figure 2: Architecture design of SAVER using contextual information

The architectural specification is provisional and subject to further research but it is included as a proposed implementation strategy for ontology-based information systems designed to increase situation awareness and operational effectiveness of emergency managers. Figure 3 shows a possible operational architecture.

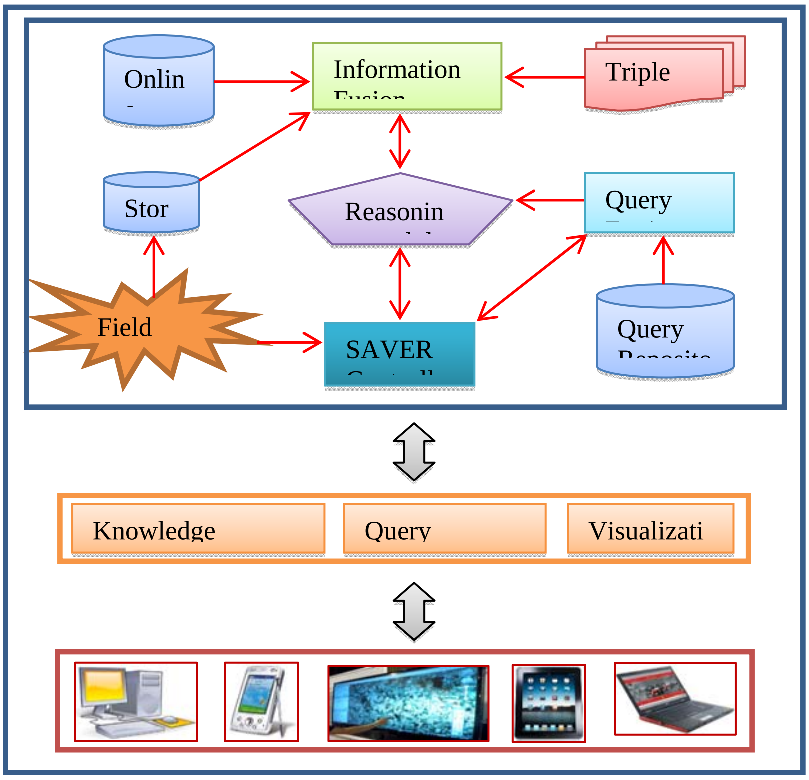

Figure 3: Provisional Architecture of an operational SAVER system

The SAVER Interface

A prototype user interface of the SAVER system was developed to see if the information provided by SAVER improved the SA of emergency managers (Javed et al., 2011). The design was also used to evaluate the human interaction (HCI) and functionality of SAVER. For Level 1 SA, the interface is designed to provide perception of information elements that are relevant and required for a particular job role and emergency phase. For example, Figure 3 shows how the interface displays the Level 1 SA information for Planning and Intelligence at the "pre-confirmation" phase of a tsunami scenario. The information about the earthquake magnitude, source location, depth etc. is provided to represent Level 1 SA at a pre-confirmation phase of tsunami, if the cursor is hovered over the icon indicating the earthquake.

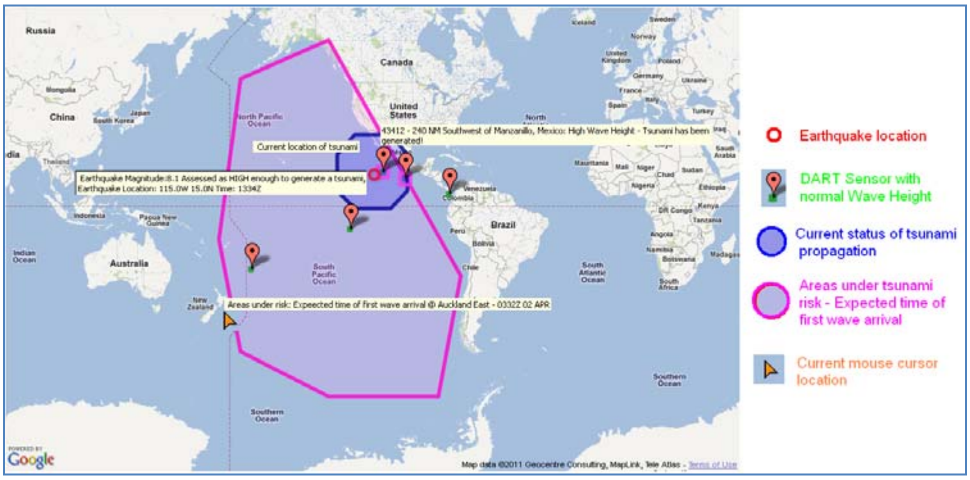

Figure 4: Providing comprehension and projection about the evolving situation

In Figure 4, a red or green colour of the circle around the earthquake location specifies whether the earthquake magnitude is of high or low intensity respectively. This interpretation of situation elements represents Level 2 SA information. Furthermore, by showing the location on the map apart from textual information also makes clear whether the earthquake source is located on or off shore.

Details of wave heights from Deep-Ocean Assessment and Reporting Tsunami (DART) data are provided in text format and the same wave attributes are displayed as a Level 1 SA item if the cursor is placed on the sensor icon as shown in the figure. Moreover, the circle around the sensor icon provides Level 2 SA by indicating whether the wave height at this sensor is *very high, high, medium, or normal* using *red, pink, blue and green* colours respectively. Moving the cursor on these circles also displays a "tool tip" note that "wave height is HIGH" if the circle is pink. For Level 3 SA, the predicted time of arrival of the wave along with the expected height is provided to managers so that they can start preparations and planning for the probable evacuation while detailed inundation models are developed. This interpretation also explains the significance of perceived information in relation to the goals and objectives of a particular job role (user). Similarly, the blue circle in Figure 3 with blue fill indicates the current position of propagating waves based on DART data.

Level 3 SA information is also provided in the form of a prediction about the future states of a situation. For example, in Figure 4, the pink area indicates the areas under tsunami risk and, when a user puts a cursor on the border of this area, the expected arrival time of the tsunami waves is shown.

Another useful SA-enhancing feature of SAVER relies on its knowledge of emergency managers' information requirements. Knowing these requirements, SAVER automatically asks for the desired information on the behalf of the person who needs it. Similarly, information about the relevant team member's SA is shared to improve common SA (TSA).

EVALUATION

Direct Measurement of SA, SSA, and TSA

To evaluate the performance of our prototype design, SAVER we objectively measured the SA of emergency managers using, and without using, SAVER. Objective measures of SA have been extensively validated to be reliable for various domains (Fracker, 1998). Data are collected at various stages of a simulation scenario by freezing the simulation and asking the participants questions about the environment (Saner, Bolstad, Gonzales, and Cuevas, 2009). The answers are then compared with the reality of the situation to determine the situation awareness as a percentage of correct answers. Questions are posed at an individual's perception (Level 1 SA), comprehension (Level 2 SA), and projection (Level 3 SA) levels of the situation.

A widely used and accepted SA measurement technique, Situation Awareness Global Assessment Technique (SAGAT) (Endsley, 2000) was used to gather data. This type of measurement directly taps into the operator's perception rather than inferring them from their behaviours, which may be affected by other factors (Endsley, 2000).

Evaluation of SAVER

In our study, SAVER was evaluated using a simulation of a tsunami episode. The simulation experiments were undertaken by 16 experienced emergency managers with up to 8 years practical experience, all of them having previously participated in either a real event or in a national exercise.

Individuals were required to complete a situation report about the prevailing situation. Information about the earthquake parameters, wave attributes like height, location etc. was provided to individuals in the form of four feeds. Each of the information feeds was followed by a question and answer session. SAVER provided information to the users using the interfaces shown above. During the task, the session was frozen and a web-based application opened a question in front of the participant. Once, the participant has answered all the questions, they can continue with the task. Participants were asked directly about the situation, e.g., what is the location of earthquake source?

In trials in which the participants were not using SAVER, they were provided with a document containing information in the format provided by the *United States Geological Survey* (USGS[1]) website used to publish earthquake information. In addition, information about the wave parameters and tsunami warnings etc. was provided in the format of Pacific Tsunami Warning Centre (PTWC[2]) website that provides DART data. To reduce learning bias, experiments were done in two parts on two different days, with more than a week apart. Out of 16 participants, eight individuals were asked to perform the experiment with SAVER first and then without SAVER and the other eight individuals were asked to perform experiments without SAVER first and then with SAVER.

RESULTS AND DISCUSSION

Table 1 shows the results of the mean % situation awareness percentages from the trials and the statistical data confirming their significance.

Construct Measured	Mean % situation awareness using SAVER	Mean % situation awareness not using SAVER	t-value	p-Value
Individual SA	82.6	73.0	2.84	p = 0.008
Shared SA (SSA)	78.5	67.3	5.95	p < 0.001
Team SA (TSA)	81.9	59.5	4.50	p = 0.003
Combined SA (TSA)	91.8	83.4	4.42	p = 0.003

[1] http://www.usgs.gov/

[2] http://ptwc.weather.gov/

Table 1: Situation awareness percentages of SA, SSA, and TSA measurements

The results show that an individual's SA is improved by using SAVER during the experiments. It seems that the SAVER's SA-oriented design improves SA by providing individuals with the information they need to understand the situation. Moreover, by processing the information on their behalf, SAVER also supports their cognitive resources like short-term memory. Similarly, sharing the interpretation of the situation and prediction about the evolving situation successfully updated the individual's SA.

The complete results (Javed et al., 2012) covering a wide range of scenarios also show that SAVER not only improves the overall SSA of teams, but also significantly improves the SSA at all three levels. It appears that SAVER's suggestions about the information requirements of team members to develop and maintain SA improves the SSA of the teams. Reminding them about their own and their team members' requirements reduces the need to remember the requirements and hence the cognitive workload and helps them to keep these requirements in mind.

IMPLEMENTATION REQUIREMENTS OF SAVER

The functioning and usefulness of SAVER has been demonstrated by the prototype but a considerable amount of work is needed to make it useable in a real environment. This section provides an overview of a broad spectrum of key development issues that need to be addressed. It covers two main areas namely: organizational and architectural requirements, and user interface requirements, and also notes testing requirements.

Organizational and architectural requirements

Requirements analysis

An in-depth requirements analysis is needed to develop and maintain the situation awareness of individuals and teams in the organization under focus. The process of requirements analysis should consider all the emergency management roles and their tasks depending upon the emergency scenarios. Moreover, multi-organization co-ordination requires agreement between organizations and comprehensive policies for information sharing and support.

Knowledge repository

The knowledge repository can consist of a LargeTripleStore[3] to provide an adequate storage mechanism for the knowledge infrastructure of the application. With SAVER, the knowledge infrastructure contains both conceptual knowledge and instance knowledge. The conceptual knowledge is represented using the concepts and relationships between the concepts, whereas the instance knowledge is in the form of individuals or values and the relationships between values and objects.

Knowledge management

The knowledge management module can make use of the tools to add, edit, and append the ontologies in the system. These changes can arise from deficiencies in the existing models or may require updating in the dynamic emergency management environment over time. Third party tools like Protégé[4], NeOn Toolkit[5], or TopBraid Composer[6] etc. can be used for ontology engineering and management.

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[3] http://www.w3.org/wiki/LargeTripleStores

[4] http://protege.stanford.edu/

[5] http://neon-toolkit.org/wiki/Main_Page

[6] http://www.topquadrant.com/products/TB_Composer.html

Reasoning module

The reasoning module exploits any reasoner for asserting the knowledge into the reasoning environment and retrieving the results of inference execution. Moreover, the reasoning module is also used to check the ontologies for any inconsistencies in the relationships or rules. The reasoner used in the current application is Fact Plus Plus, which is simple to work with and efficient for small size ontologies. However, various other reasoners, for example, Racer, Pellet, Hermit etc. can be evaluated as alternatives.

Query repository

The query library consists of a collection of predefined query templates that may be of generic use across multiple operational contexts. Currently, SAVER uses only a few queries saved in SAVER Controller (next section) for different situations and roles. However, a wide range of queries can be saved using ontological characterization to facilitate more meaningful and rapid selection and retrieval. In addition to this, the results of most generic queries can also be saved for quick retrieval.

SAVER controller

The controller component of SAVER is like the central processing unit of a computer. It can be activated by feeds from the sources to which it is subscribed or the user can manually activate it by adding an event into SAVER and asking it to monitor some specific information sources. SAVER controller can then make use of available information, the reasoner module and predefined queries to provide the situation assessment to the users. The SAVER controller works as a communication channel between the users and the SAVER system. All messages, notifications and event management is done by the controller.

Information fusion module

An information fusion module can be used to integrate the information from diverse sources including information from within the SAVER system, for example from ontologies (TripleStore). The information is saved in the form of instances of ontologies and processed using a reasoning module to draw inferences according to the situation requirements.

Computing and hosting requirements

For a system like SAVER, quality and availability of service are very critical for successful usage and trust emergency managers. Both of these mandates come with huge cost and dedicated network resources. However, the cost can be reduced by using computing and storage facilities provided by cloud computing. In cloud computing there is a significant workload shift. Local computers no longer have to do all the heavy processing when it comes to running the huge applications (SAVER using large ontologies will require a huge amount of computing power). Moreover, using cloud computing, the hardware and software demands on the user's side also decrease (Strickland, 2008). The only thing the user's computer needs to be able to run is the cloud computing system's interface software, which can be as simple as a web browser.

The cloud operates in a secured environment and the cloud service providers assure its security. All the processing is done on the server side and hence the client side does not require the specialized hardware and software for running and storing large applications. The reliability (and hopefully the security) of SAVER services will be assured by the cloud service providers. SAVER will become scalable in terms of storage space as well as the power it requires for processing the large and complex ontologies. Therefore, it can easily be extended to many other types of disaster contexts, organizations, and thousands of users over the Internet.

Graphical user interface (GUI) requirements

End user requirements

The design and implementation of the GUI components need to take into account the specific visualization requirements of different user groups. Moreover, the ergonomic configuration of such interfaces must consider the cognitive requirements of the end users. This is of significant importance for providing the interfaces to improve the situation awareness of individuals and teams. Detailed user interface requirements are needed for this purpose. This analysis should involve emergency managers in the design process and assure the availability of information in the format required by them.

SA, SSA and TSA oriented visualization

Interfaces should be designed by considering the factors that affect the situation awareness. For this purpose, as suggested in the design of the SAVER prototype, information should be arranged according to the goals and tasks of the roles. Moreover, the format of the information, i.e. pictorial, map, or text, should be used according to the requirements of the task. Adequate interfaces for chat and co-ordination should be provided along with the shared interface providing the overall up-to-date picture of the situation to improve the SSA and TSA of the team. Hence, SA, SSA and TSA of the individuals and teams should be improved by providing personalized interfaces for each role.

Query visualization

The process of specifying appropriate queries is vital in the exploitation of knowledge-based systems. The queries central to the requirements of situation awareness need to be stored in the query repository as discussed above. Appropriate interfaces should be designed to allow building and execution of the customized queries. The interface should provide a way to build semantically enriched queries to take full advantage of an ontology-based system. A very useful aspect in this regard can be the graphical query interface since it does not require the users to know the knowledge architecture of the system. This area is still under research.

Use of mobile devices and touch screens

With the extensive improvement in the computing and graphical capabilities of mobile devices, they are now perfect candidates to keep the users up to date with the prevailing situation anywhere any time. SAVER is a web-based application; therefore, it can be accessed on any device that is capable of running an Internet browser application. However, there is a need to develop adaptive interfaces so that a device can display information according to its capabilities. Moreover, large displays and multi-touch screens provide a new mode of visualization and human computer interaction. Large screens can be used to provide a shared overall tactical picture of the prevailing situation improving team situation awareness. Similarly, touch screens can reduce the amount of learning required for information retrieval using textual queries or time consuming input by ordinary devices (e.g. keyboard, mouse, light pen) since maps and graphical components can be directly touched, dragged and dropped for input in a natural way. A combination of graphical query interfaces with the multi-touch screen would be an astonishing application of both these technologies.

Testing requirements

SAVER has been evaluated for improving the situation awareness of individuals and teams. However, before using the operational SAVER in real events, it needs to be tested with real data for accuracy, especially with large data sets. This can be done by using SAVER in multi-organizational exercises or in actual events as a dummy system. A detailed functional testing will verify that it provides the functionality to perform all the required tasks. Non-functional testing will clarify other aspects like availability, scalability, performance, security, etc.

CONCLUSION

This paper describes the design and development and evaluation of the SAVER system that aims to improve the SA, SSA and TSA of emergency managers in emergency situations. The evaluation of a prototype shows that SAVER does significantly support and improve these forms of situation awareness at the perception, comprehension and projections levels. The use of such systems can enhance the effectiveness and efficiency of decision-making and collaborative task performance. The paper also describes the implementation requirements of an operational SAVER system.

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