Enhanced Navigation at Sea: an augmented reality-based tool for bridge operators

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Synopsis

This paper presents the design framework, in which a Decision Support System (DSS) tool has been developed to assist the bridge operator during a challenging navigation condition. The present project would be another step for using state of the art, IT devices and hardware, to increase safety at sea mainly focusing on both collision and grounding avoidance. In this paper, the modules to detect an obstacle and to calculate the evasive route are based on a customized simulation model: such a model is able to represent the dynamic behaviour of a ship, including hydrodynamics, propulsion, and control effects. The suggested route selected by the decision support system and some environmental parameters coupled with some of the ship parameters are visualized on a smart "virtual bridge" exploiting virtual reality techniques. A suitable graphical interface has been developed and installed, in order to enhance the situation awareness.
The project also focuses on the communication architecture, which relies on a publish-subscribe paradigm and is responsible to forward ship control parameters both to the virtual bridge and towards an ashore control centre, either for supervising or for remote control.
Overall, both the potentiality and the limits of the proposed system have been critically discussed.

Keywords: Autonomous Ship; Marine Control System; Virtual Reality; Situation Awareness; Maritime Mobile Communications; Decision Support System

1. Introduction & Motivation

This paper presents the studies for the development of a simulation-based Decision Support System (DSS) integrated with the "Smart Bridge" that allows the display of information, appropriately selected and processed, in order to enrich the information content of the perceived reality. The user of the selected application is the bridge watchkeeping officer and his/her 'twin' in a shore-based ship control centre. In this first application, the information presented by the virtual reality regards the collision avoidance. The DSS is based on two modules: the first identify the target and the second calculate the evasive course. The suggested route and some key parameters are visualized on a screen exploiting virtual reality techniques. The same information are made available ashore through a dedicated communication. Unlike others, this work aims to investigate the benefit of a system that integrates different modules: a ship simulator, communication strategies, and a screen in order to offer to the bridge operator a valid support for a safe navigation.

In order to test the system either in the office or in the laboratory, a realistic navigation scenario has been simulated.

A simulation model that is able to represent the dynamic behaviour of the ship, including hydrodynamics, propulsion, and control effects, computes the evasive course. Dynamic simulation represents one of the most useful ways to predict the dynamic behaviour of ship systems in a virtual environment. Numerical simulation of propulsion systems requires a detailed knowledge of the system and great commitment of human and computational resources (Altosole et al., 2012). Dynamic simulation gives the possibility to investigate, at the design stage or without having the real ship availability, the transient behaviour of the ship during manoeuvres. It gives the possibility to test and optimize several ship parameters, further it allows a reliable development of both control and decision support systems.

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In recent years, many studies highlighted the advantages deriving from navigation through the three-dimensional visualization of cartography (Goralski, et al. (2011)). The scientific community has reserved particular interest to Augmented Reality (AR) application in the maritime sector (von Lukas U et al. (2014)).

However, nowadays, Augmented Reality studies, related to the maritime field, focus on overlaying additional information on Virtual Reality environments (T. Butkiewicz, 2017). (Grabowski, 2015) has also studied the new challenges related to the impact that these new technologies have generated in the maritime field and the contribution that AR technology can provide in safety-critical systems (Grabowski, et al. 2018).

The proposed DSS integrates state-of-the-art simulation techniques, communications, and virtual reality to obtain a new smart system for a safer navigation.

2. Model-based Design & System Architecture

In the authors' opinion, a realistic representation of the controlled system is necessary to study a new control system feature. Therefore, in order to study the effectiveness of the developed methodology, a multi-domains simulation platform able to represent the dynamic behaviour of a ship and the communications infrastructure in the time domain was developed. With respect to the results of previous work available where systems are modelled one at a time and with very limited interactions, here the aim is to merge into one platform three ship macro-systems that contribute to the global ship representation: the ship dynamics, the communication infrastructure, and the control system. In this way, it is possible to capture the mutual interactions between all the elements involved, considering the ship as a system of systems. Moreover, real hardware is included in the simulation loop i.e. the "virtual bridge". These four elements together create the possibility to enhance the situation awareness during ship operations. The peculiarity of this work is a system engineering approach to bring together all disciplines involved to represent a unified view of the system. A sketch of the simulation platform layout is shown in Figure 1.

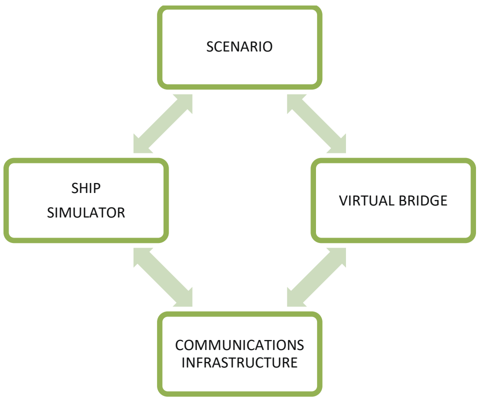

Figure 1: System Layout.

The system architecture is composed of four different modules, each interacting with the others. The ship simulator creates the time histories of the main variables needed for the control of the ship (i.e speed, course, shaft revolution, etc.). Inside the ship simulator, the collision detection and avoidance modules work in real time. The outcomes of the ship simulator are directed to the scenario in order to visualize in a 3D environment the ship motions. The scenario is customizable in terms of the manoeuvre, the main elements (both fixed and moving obstacles), and the geographical information, i.e. the bathymetry. The smart bridge is the real hardware (a screen). It receives the main information from the scenario and from the ship simulator and, after processing this information, it visualizes the main information used to perform an evasive manoeuvre. Thus the 3D visualization works as a tool to support the user to take decisions and to enhance his the situational awareness. All the information are managed and transmitted by the communication infrastructure. The four modules are explained in detail in the next sections.

2.1. Ship Simulator

The simulator is a software platform that allows the study the vessel behaviour during transient conditions (acceleration, deceleration, etc) and during steady-state conditions (constant speed navigation) as well as the analysis of the mutual interaction between all the elements involved. To reach the goal, all the main ship macro systems were joined together to adequately describe the global ship behaviour: the ship manoeuvrability, the propulsion plant, and the control system. Each macro system is composed of different elements; each of these elements has been schematized and modelled using the differential equations that govern their physical behaviour and represent their functions.

Table 1: Simulator sub-system

MACRO - SYSTEMS	SUB-SYSTEMS
Manoeuvrability	Hull
	Rudder
	Appendages
	Propeller
Propulsion Plant	Main Engine
	Gearbox
	Shaft line
Control & Guidance System	Propulsion Control System
	Collision Detection
	Collision Avoidance

The different sub-models have been studied and developed with different degrees of detail. The simplest way to schematize a system is by using a table of parameters and algebraic equations that identify the system behaviour in steady-state conditions (i.e. propeller). On the contrary, detailed analysis requires computational efforts that do not fit with the real-time requirement. The complex and more realistic approach, used for the most of the elements, is to model the system with its physical equations, both algebraic and differential (i.e. ship hull force, control system, shaft line dynamics). With this approach, a large set of parameters must be taken into account, and this itself can be a difficult obstacle. An intermediate approach could be obtained by merging tabular models and algebraic/differential equations to produce a quasi-static model (i.e. prime mover).

The problem can be summarized by the following set of differential equations (Zaccone & Martelli, 2018):

$$M\dot{\nu} + C(\nu)\nu = \tau_H + \tau_P + \tau_R \tag{1}$$

$$2\pi I \frac{dn(t)}{dt} = Q_{eng}(t) + Q_{fric}(t) + Q_P(t) \tag{2}$$

$$S_i(t) = K_{P\_i}\ e_i(t) + K_{I_i}\int_0^t e_i(t)dt + + K_{D\_i}\frac{d}{dt}e_i(t) \tag{3}$$

The equation of ship motions (1)is here expressed in vectorial form as for example in (Martelli,2015). The propulsion plant dynamics is described through the differential equation of the shaft line (2); solving this equation over the time domain for each shaft allows the obtainment of the propulsion plant behaviour in terms of shaft line revolution regime, $n(t)$. Shaft line acceleration depends on the engine, friction and propeller torques, Q_{eng}, $Q_{fric}$and Q_p, respectively, and on the total polar inertia I of the drive line. In the case of a twin-screw ship, where the two shaft lines can be used independently from each other, this is needed because in the case of tight manoeuvres, strong asymmetries in terms of shaft loads can be experienced.

The local engine governor control system is represented by a set of equations, whose form in many cases describes a PID controller, like the one presented in Equation (3), describing.

Detailed information about each sub-module of the simulation platform is reported in (Donnarumma et al., 2015, Alessandri et al., 2015). Moreover, the validation of the simulator model, based on a dedicate sea trials campaign, is presented in Donnarumma et al. (2017).

2.2 Network Simulator

All the software modules used for the simulation of the network infrastructure were developed to be interfaced with the other modules of the simulation framework.

The Publisher and Subscriber Proxies modules are implemented in Java. The configuration parameters for the modules are defined in a file encoded in XML, whose correctness is validated through an XSD-based (XML Schema Definition) schema. Some of these parameters are the network parameters and a field to enable a secure connection toward the broker. Precisely, the network parameters are the IP address and the port number used to exchange data with the broker, instead, the secure connection field is a flag that enables the use of the TLS protocol if needed. Also, in the file, there is the list of available topics and the pair of username and password used for the authentication with the broker. The Broker module is based on the open source MQTT broker Mosquitto (https://mosquitto.org/). Mosquitto is widely used in several research projects focused on the Internet Of Things. It supports client authentication via username/password and allows secure connections through the TLS protocol. The effects of the Satellite Channel were simulated by reproducing a high propagation delay and the effects of the access to the channel in a time division way. The software code has been integrated into the module of the Ashore Subscriber Proxy. In fact, as the figure 2 shows, this module only perceives the effects of the satellite channel. The propagation delay due to the satellite is simulated by delaying data transmission to subscribers by $250\ ms$. Instead, the effects of the time division access were simulated by forcing the Subscriber Proxy to read from its data buffer at a fixed frequency. Precisely, in a satellite link with a time division access, a user can transmit one data packet always within a pre-established time slot. Also, this time slot is made available once every $13\ ms$, so the read rate is forced to 1 packet every $13\ ms$.

3. Communications Infrastructure

In this section, it is discussed the communication infrastructure developed to convey the information generated by the ship control systems, such as the engine controller or the wheel controller, toward the DSS. The proposed architecture is oriented to the decision support service of the bridge operator, so, it is essential for the ship control systems to send toward the DSS the information instantaneously once they are generated. It is assumed also that data of the ship control systems is displayed on a virtual bridge viewer, to support the bridge operators. The DSS and the virtual bridge viewer can be placed either on board the ship or in an ashore control centre, it is possible to call these DSS entities and viewers entities. The scenario described above is a complex scenario where the information generated by several ship control systems are shared with different DSSs entities and viewers as well. We can guarantee reliable information sharing endowing the communication architecture with the publish/subscribe paradigm (Fiege, 2003; Marques, 2006; Leontiadis 2007). This kind of paradigm allows to the ship control systems (publishers) to send the information generated periodically (time-driven policy) or in face of events (event-driven policy), independently from the DSSs and viewers entities (subscribers). This means that data producer and recipients of the information can operate in a non-concurrent way, that is, they can communicate without necessarily being connected. This is made possible by the third party called the broker.

The broker collects the data when generated by the publishers and send them to the subscribers. The broker can send data with several degrees of reliability. For example, the information is sent when the subscriber is available, the information is sent when the subscriber is available. The publish/subscribe paradigm can be used to achieve many-to-many interactions, but in the proposed scenario, it is used to achieve one-to-many interaction. In this case, the broker installed on the ship (one) and the DSSs (many), as well as between the broker and the viewers. Furthermore, in this case, the publish/subscribe paradigm is used in a topic-based way. This means that the broker can make available to the subscribers the published data in a clustered way, where each cluster is called topic. The topic contains a subset of all the published data, which can be received by a subscriber to accomplish a given task. Before it can receive topics from a broker, a subscriber needs to perform a subscription, stating the topics of its interest. The communication protocol adopted in our communication infrastructure to accomplish the functionalities described above is MQTT (Stanford-Clark, 2013).

MQTT is a protocol that allows any control and data acquisition system to access functionalities of the Internet of Things (IoT) platforms by the publish/subscribe paradigm, bringing many powerful benefits such as:

- Distribute information more efficiently
- Increase scalability
- Reduce network bandwidth consumption dramatically
- Reduce update rates to seconds
- Very well-suited for remote sensing and control
- Maximize available bandwidth
- Extremely lightweight overhead
- Very secure with permission-based security
- Saves development time

Figure 2 shows the communication infrastructure developed for our scenario, we can see that the data generated by ship control systems are conveyed to the Publisher Proxy. This is a software module able to receive data also from systems that are not compliant with the MQTT protocol, all received data are then encapsulated in MQTT messages. In this way, we can guarantee the interoperability among the ship control systems that are not natively compliant with the MQTT protocol. For the same reason, we have introduced the Subscriber Proxy. The broker is again a software module installed on-board of the ship. The broker is also a software module installed onboard on the ship. We have chosen to install it on the ship to minimize the delay as much as possible during the topics transmission toward the DSSs entity and the viewers onboard on the ship. The broker can be installed also in a control centre on the ground, but the communications between the ship and the ground are performed with satellite link, hence the delay can be remarkable. Nevertheless, the satellite allows communications with the ship wherever it is. Furthermore, the ships are already endowed with satellite communication systems. In the section Ship Simulator, we discuss the implementation of the software modules involved in communication infrastructure.

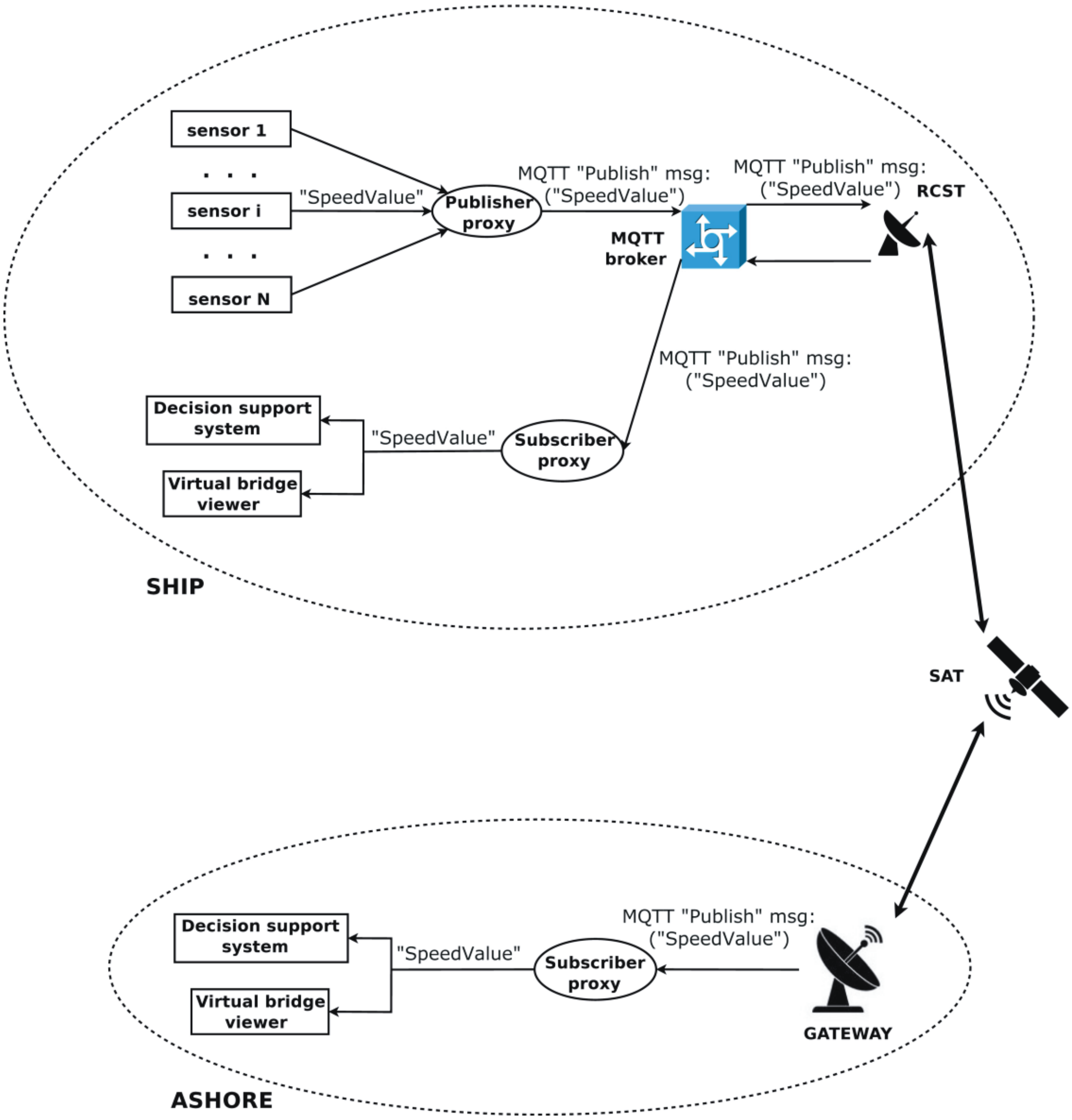

Figure 2: Communication Infrastructure.

4. Virtual Bridge Viewer

The system developed in this project includes the implementation of a Virtual Reality (AR) application to support offshore navigation. The system provides the bridge staff with various information directly from the AIS, ECDIS, ARPA onboard systems, but also it provides users whit with a forecast of possible evasive routes processed through the simulator developed in the laboratory of the Marine Engineering Department of the University of Genoa. The information is available on the display in graphical or textual form, choosing the more suitable representation for each type of data. On the display you can also view information related to navigation and special hints needed to avoid collisions with obstacles in the proximity (for example other ships or rocks), using data computed by a simulator able to detect possible collisions and to suggest manoeuvres to avoid them. The use of

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this particular tool allows the bridge operator to see both a virtual realist world (the open sea around the ship) and the digital information pertaining to it, in order to support the operator in his safe navigation activity. A similar interface is available on the ground control station, running on a desktop system and using the same information available which is onboard the ship, so even ground operators can monitor what is happening in real time and eventually support the operator on the ship. Figure 3 shows a representation of a first concept of the Visualization module with a representation of data coming from the simulator developed by the University of Genoa. The displayed data have been selected by a team of experts as the most effective to support safe navigation. Data representation can vary in a collision avoidance situation when some data can be highlighted to draw attention on risky elements and critical parameters.

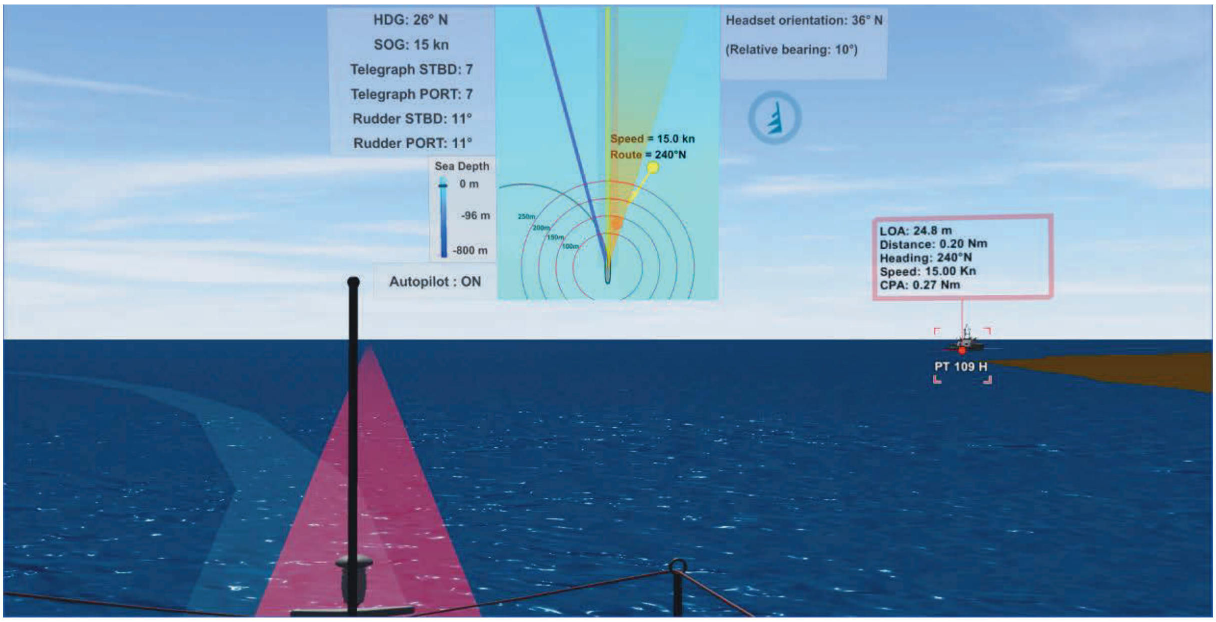

Figure 3 Viewer concept

The information available on the display is already available on board with other systems. The added value of the Smart Bridge Viewer is represented by the fact that different information coming from the complex onboard systems is available for the watchkeeper while she/he is monitoring the real environment from the bridge. Each operator can customize the data visualization. This helps the operator to gain situational awareness, acquiring essential data while observing the real world.

5. Scenario Building & Results

The application scenario selected to test the system involves a ship that serves as a multi-mission patrol. The chosen ship is an offshore patrol vessel. It has a length of 91.2 m, a width of 20.5 and a displacement of 3500 tons. The two diesel engines of 2300kW @ 1050 rpm each, guarantee the achievement of a maximum speed of 18 knots. There are also two electric propulsion motors of about 300kW each, which provide good flexibility to the propulsion system configuration: CODLOD (COmbined Diesel eLectric Or Diesel). The selected vessel has many advantages, including a huge versatility determined by its Search and Rescue (SAR) operating profile, it is a ship designed for anti-fire, anti-pollution, recovery, and rescue operations. The tool will have the function of increasing the performance of the bridge operators through additional digital information. The test case consists of detecting an obstacle and plan an evasive manoeuvre, as it is a situation that provides an analysis of the results.

The test consists in the launch of an application available on board the ship that supports the operator in carrying out the appropriate manoeuvres for example the return to port and another application displayed on a workstation of remote control that allows monitoring the operations by another point of view, an example of a virtual reality environment has been developed, as shown in Figure 4.

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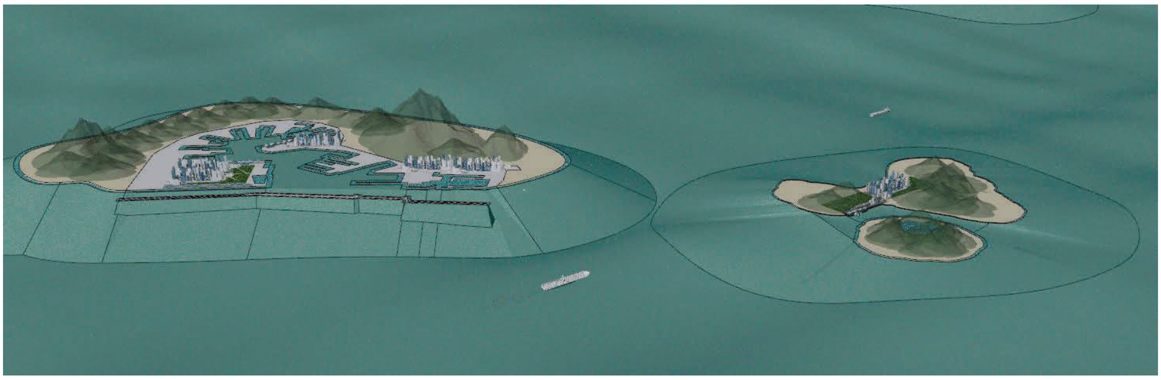

Figure 4 Example of 3D scenario visualization

6. Conclusions

The system described in this paper is effected by few limitations, the application is not really user-friendly at first use, and needs preliminary training. Moreover, the effectiveness of the tool is related to the "digitalization" level of the user. The proposed concept, however, is thoroughly valid because different data from the onboard systems and the simulator are integrated into the vision of the bridge operator who has to sometimes make fast decisions regarding manoeuvres and solutions to avoid collisions and ensure safe navigation. This is obviously only the starting point and considerable progress can be made by investing in improving the individual modules. The display part can be improved by evaluating the user perception regarding the information shown. Another step is to improve the decision support system introducing a new paradigm as Ontologies and Reasoners.

7. Acknowledgements

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