Geovisual Analytics Environment for Supporting the Resilience of Maritime Surveillance System

Gabriel Vatin, Eric Rigaud, Aldo Napoli

Geovisual Analytics Environment for Supporting the Resilience of Maritime Surveillance System

Gabriel Vatin, Eric Rigaud, Aldo Napoli
MINES ParisTech
Center for research on Risks and Crises
Sophia Antipolis, France
{gabriel.vatin, eric.rigaud, aldo.napoli}@mines-paristech.fr

***Abstract* — This paper presents an original approach for supporting the resilience in Maritime Domain Awareness, based on geovisual analytics. While many research projects focus on developing rules for detecting anomalies at by automated means, there is no support to visual exploration led by human operators. We investigate the use of visual methods for analyzing mobility data of ships. Behaviors of interest can be known (modeled) or unknown, asking for various ways of visualizing and studying the information. We assume that supporting the use of geovisual analytics will make the exploration and the analysis process easier, reducing the cognitive load of the tasks led by the actors of maritime surveillance. The detection and the identification of threats at sea are improved by using adequate visualization methods, regarding the context of use. Our suggested framework is based on ontologies for maritime domain awareness and geovisual analytics environments, coupled to rules.**

Keywords — maritime domain awareness; analysis support; resilience; geovisual analytics; ontologies.

I. Introduction

On January 13th 2012, along the Italian coast, the cruise ship Costa Concordia sank while it was sailing too close from the shore. Finally, 32 human casualties were declared, and the costs of this accident represented more than 750 million dollars for insurance companies. Along another continent, the International Maritime Bureau reported 40 pirate attacks in the Gulf of Guinea in 2013, overtaking the piracy threat along the coasts of Somalia [1]. Most of their targets are related to the oil industry, a very sensitive business at world's scale. These two examples show the very diversity of threats and risks at sea: these can come from human intention (such as piracy, pollution, illicit activities, etc.) dealing with security, on non-intentional errors (collision, grounding, etc.) dealing with security.

In order to improve the management of these risks at sea, many solutions can be undertaken. These various strategies can be advances in the jurisdiction at sea, in the social organization within the whole maritime surveillance system, or technological improvements. Within this last strategy, the first requirement of new technologies is to reach an improved analysis of the behaviors of ships, along with an integrated surveillance system.

For these security and safety questions, the European Union has led until now several research projects on two major questions: improving the captors for surveillance, and improving the surveillance tools with advanced recognition of threats or unusual behaviors [2]. Intelligent systems for the analysis of maritime traffic information have resulted from this collaboration between European academics and industries, such as I2C and Reconsurve [3]–[5]. These projects are European equivalents of the PANDA program (from DARPA, USA) to support understanding and predicting vessel behaviors, and identifying anomalies. In this context, several maritime rescue coordination centers (MRCC) take part in the action of surveillance and decision-making, for enhancing the safety and security of maritime area. These several actors, technologies, procedures for decision-making constitute a whole system centered on the maritime culture.

However, this whole system of maritime surveillance is still facing complex problems, due to the recurrent information overload during the analysis process [6]. Moreover, the risks to be monitored are often very complex in their nature and not always known in advance: for instance, drug traffic is yet very difficult to recognize among the other trajectories. For these reasons, much research is still ongoing in the field of Maritime Domain Awareness (MDA), which is defined as the constant perception of maritime environmental elements with respect to time and space, the comprehension of their meaning and the projection of their status after some variable has changed [6]. Thus new axes for reflection should be addressed, in order to improve the process of decision-making. Among these, the resilience of maritime surveillance system has a major role for further research: it is the capacity of a system to recover quickly from major changes, while still keeping its main functionalities to a certain level [7].

Since maritime surveillance require a constant effort of monitoring and analyzing huge amount of near real-time information, often of various types (meteorology, bathymetry, mobility of ships, etc.), we assume that allowing resilience within this system should be supported by improved monitoring and analysis tools. The analysis step led by surveillance operators, which would be supported by advanced and intelligent technologies, would make this process easier and safer, for better decision-making and improved reactions to threats [8].

In this paper, we present the major contribution of geovisual analytics for supporting the resilience capabilities in the context of Maritime Domain Awareness. In section II, we highlight the notion of resilience in the context of Maritime Domain Awareness, and the key role of geovisualization toward these capabilities. Section III introduces our proposed approach for supporting in the use of geovisual analytics in threat analysis. We illustrate the use of this framework in section IV, with selected risk scenarios. Section IV concludes this paper.

II. Maritime Domain Awareness & Resilience

A. Resilience in Safety Management

Resilience is an integrative concept that appeared in scientific thinking in the 21st century, and encompasses two main ideas: response to stressful events and sustainability of systems in coping with stressful events [9]. There is no consensus on a common definition of system resilience. Resilience is sometimes considered as a process, as a characteristics of system, as a dynamic of development, as an outcome, and sometimes all of the above [10]. To be resilient, a system has to be exposed to significant threats or severe adversity and achieve a successful adaptation despite negative conditions [11]. Resilience related definitions, models and artefacts vary according to the diversity and the complexity of systems (technological devices, individuals, groups, working situations, organizations, communities, states, territories, etc.), of threats (natural, technological, anthropic, economical, anticipated, surprise, etc.) and of adaptation modes (routines, compliance to rules, improvisation, return to a stable state, transformation, etc.).

Theories of Resilience has been developed with perspectives of improving safety performance and safety management systems in management sciences [12]–[14], in safety sciences [7], [15] and in disaster and crisis management sciences [16]. Some works on the definition of resilience are related to specific capacities: "capacity to cope with unanticipated dangers" [12], "capacity to improvise", to "bounce back" [13], "monitoring the boundary conditions of the current model for competence and adjusting or expanding that model to better accommodate changing demands" [17], whereas other works aim to integrate all capacities that are required to be safe: "the intrinsic ability of a system to adjust its functioning prior to, during, or following changes and disturbances, so that it can sustain required operations under both expected and unexpected conditions" [7].

As no system can continue to exist if it is unable to respond to unwanted situations happening, this ability is one of the core abilities of system resilience. In order to respond, the system must first detect that something has happened, then identify the event and recognize it as being so serious that a response is necessary, and finally know how to respond and be capable of responding both timely and effectively so that can bring about the desired outcome [7].

In the context of maritime surveillance system resilience, the detection and identification of threat are major research issues.

B. Detecting and Interepreting Maritime Threats

As it was presented in the introduction of this paper, maritime surveillance is composed of several actors dealing with maritime information, from monitoring to decision-making and actions. Enhanced maritime domain awareness is a key for improving the security and safety of this area. Thus, many projects have been led in Maritime Intelligence, Surveillance and Reconnaissance (MISR). In MISR activities, three main goals are at the heart of these projects: finding ships that we don't know about, finding known ships with unusual behaviors and finding if security concerns are raised by the cargo or the crew [18]. These stages of surveillance and recognition of threats pass through an accurate knowledge of the surveillance coverage and the many trajectories of ships, the analysis of their single behavior and attributes, and the interpretation regarding possible risks.

Using the knowledge of maritime experts concerning what is usual and what is not, hence knowing what could be a dangerous or unusual behavior, has been a major point in research these past few years. Intelligent systems for automatic identification of unusual behaviors have been proposed, in both historical data with data-mining for discovering new patterns [19]–[21] or real-time data for monitoring known patterns [4], [22]. Detecting unusual behaviors is a first step, requiring afterwards the interpretation of this different profile, for identifying the risk. Some works have been proposed for characterizing these behaviors based on taxonomies of movements and attributes, giving meaning to the ship's behavior [22], [23]. However, the acceptation of such technologies for detecting unusual behaviors and identifying risks is still an essential concern. Indeed, human operators have more trust in what they analyze and discover on their own, rather than fully automated process [24]. It is partly due to their work habits, where they rely on their own experience in maritime surveillance for decision-making.

Yet, intelligent technologies for supporting the analysis tasks and decision-making process are fundamental for enhancing the detection and interpretation of threats. Indeed, a single human operator cannot get the whole link between information, for well-known cognitive matters [25], [26]. Therefore, solutions such as problem solving environments and visual analytics have been introduced for supporting the cognitive load of users.

C. Support of Analysis for Problem Solving

We have seen that the resilience of a system requires a strong collaboration between human stakeholders and assistance to decision with powerful computation, such as with Joint Cognitive Systems, which were introduced by Hollnagel and Woods [27]. Therefore, there is a real need of supporting the human exploration and analysis of information, with methods coming from the domains of information visualization (InfoVis) and geographic information visualization (GeoVis) [28], [29].

Visual analytics, which is defined as the *science of analytical reasoning facilitated by visual interactive interfaces* [30] is a solution of great interest for both involving stakeholders in the analysis of data, and resulting in knowledge of great interest for decision-making [31]. The role of geovisual analytics (GeoVA), the application of visual analytics to geo-information, has already proved great success in the exploration and analysis of mobility information [32]. The several methods of geovisual analytics that have been proposed by researchers until now constitute a solid background for exploring various questions and problems dealing with exploration of spatio-temporal events; as it is the case with the behavior of ships in maritime surveillance. The use of such techniques can therefore bring new solutions, or new outcomes, to the actors using it [24], [28], [33].

However, the new challenge is now to investigate what would be the proper visualization(s) and interactions to explore a certain problem, according to the object of interest or the risk to look for. Whereas much work has been done on adapting the visualization to the data type, few have been interested in the matching to exploration tasks [34]. The environments for geovisual analytics that have been developed cannot be applied to any type of data, for any questions, and are not usable by everyone, depending on the profile [35]. Therefore, there is currently a lack of support environment for leading this analysis, allowing selecting the proper visualization according to the context of use. The analysis led by stakeholders in risk assessment requires a support in the use of GeoVA, such as problem solving environments (PSE) were defined [36]: a *computer system that provides all the computational facilities to solve a target class of problems*. The authors specify that such a PSE should help one choosing the best solution methods among many for a given problem, and keeping track of the problem solving tasks. This way, they make problem solving much faster than it usually is. According to the definition of resilience that was stated in previous section, we assume that a “geographic PSE” can improve the detection and identification of risks.

In next section of this paper, we propose a framework for supporting the use of GeoVA, in order to improve the analysis of mobility information of ships at sea. This way, an enhanced and easier analysis would reduce the work load of human stakeholders, therefore improving the detection and interpretation capabilities of an operator in maritime surveillance. Next section present our proposed approach, that is later illustrated in section IV.

III. Supporting the Resilience of Maritime Domain Awareness with Geovisual Analytics

Schiewe defined geovisual analytics as a *linkage of visual and computational methods and tools for extracting hypotheses and information from spatial data* [37]; it is essential to have in mind that hypothesis and conclusion cannot be drawn from simple spatial data. It is the combination of spatial information, temporal information and other attributes of the studied objects, that allows extracting patterns of interest. Therefore, Kraak explained that GeoVA has to synchronize spatial, temporal and attribute visualizations for an effective exploration of the information [38]. In order to propose adequate visualization for specific risk exploration task, these three views of the information must be considered when reviewing the risk type and the task to be led with visual analytics. In the rest of this paper, we distinguish the visualization methods, or spaces, with the geovisual analytics environments (GeoVAE). These are the combination of several visualization spaces which can be used together, allowing dynamic linkage and redundancy of the information within these spaces.

As a start to this process, we define a Situation as the context of use: it is composed of a certain user, a task or a collection of ordered tasks that may be relative to a particular risk, the data that are available to the use. The user is defined by his profile, which gives indication of interest for further study of his skills: his job and place of work (i.e. place where he uses the visualization), his knowledge of the data (experience in maritime domain), his scientific education and his technological abilities (according to available hardware, or his own experience with information visualization). To limit the possible values of these last three attributes, these are described on a scale from 1 to 3; 1 being *Basic* and 3 being *Expert*. These simple values will be used later for describing the rules for using visualizations of interest.

Our framework uses four main components for supporting the analysis of information: (1) the model of the current situation, (2) the model of GeoVA domain for maritime domain awareness, (3) the rules that allow matching the situation to the various solutions, and (4) the reasoner that applies these rules. For knowledge representation of GeoVA, and intelligent machine reasoning, a formal model was meant to be used. For this reason, we chose to use ontologies for the knowledge representation, using formal OWL language based on RDF. Ontologies are based on a formal and explicit specification of a shared conceptualization [39], making this representation of knowledge re-usable by other communities. Moreover, the use of ontologies also allows setting up rules from the developed concepts, with SWRL formalism. Rules are based on “if, then” statements using the existing concepts and individuals in the ontologies.

The formalization of GeoVA is based on the most used visualization spaces in current surveillance tools and in most common GIS functionalities. Also, we chose to take into account the most recent work achieved in GeoVis community for advanced visualization of trajectory information and their limits, such as the space-time cube [40], trajectory wall [32, p. 201] or self-organizing maps [41]. This allows proposing new ways of visualizing the information and discovering new knowledge, for the corresponding context of use regarding their limits: amount and time of data, user’s profile and acceptation of technology, etc.

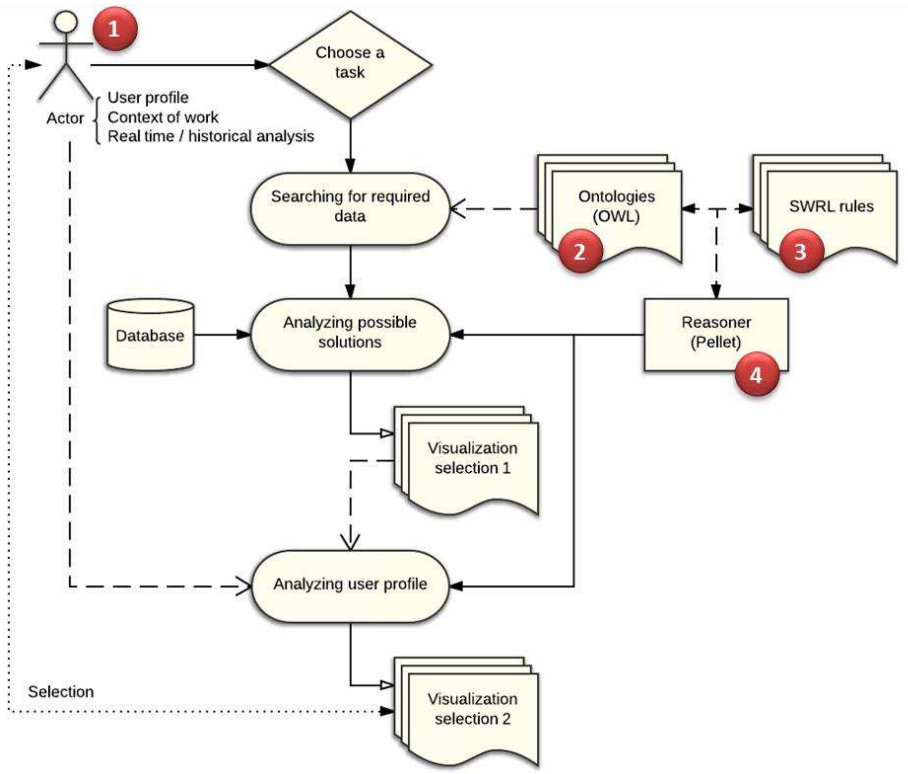

Fig. 1. Use of the ontology and rules in the reasoning process.

Figure 2 shows how these four components are used, and at which stages the SWRL rules are employed. The user defines a situation with his own profile and context of work, but also if the data he is dealing with are real-time or historical information. Choosing the task to be performed, for instance analyzing the trajectory of a fishing vessel, will ask for certain data defined by the ontology. According to the successive stages in the task, which are also pre-defined in the ontology, an automatic exploration of the visualization possibilities is made to find: which visualizations allow these data, and which visualizations allow these task stages?

From this first selection of visualization methods, based on pure visualization theory, a second selection results from the user profile, which may require simple visualization methods: for instance no use of 3D or no complex statistics. The time of the data (real-time, historical) also acts as a filter on the first selection, as many visualization methods cannot be applied to real-time data. The second selection of visualization methods provide adequate solutions for the data, the user profile and hits context of use, and the exploration task to be led.

In the next section, we show how to use this framework, with a behavior of interest, which cannot be interpreted on its own. We also present some geovisual analytics solutions that have been developed with the use of a web GIS (Geographic Information System), to illustrate a few examples for visualizing spatio-temporal information.

IV. EXPLORING PARALLEL TRAJECTORIES

A recurrent mantra in visual analytics is "Detect the expected and discover the unknown" [30]. In terms of the Cynefin model for classifying events in four categories (simple, complicated, complex and chaotic) [42], this mantra could be translated as: *visual analytics provide methods to recognize simple and complicated situations, and to discover relations in complex situations*.

In order to illustrate the real contribution of our system to the resilience in threat detection and identification, we choose to explore a case that an operator would not identify by himself and which couldn't be anticipated.

This scenario is defined by two ships in the open sea, approaching and then having parallel trajectories. This configuration of trajectories can be found in several usual or unusual events, which could not be predicted by the system. For instance, (1) ship A attacked by pirate ship B, (2) A rescued by B, (3) parallel fishing (forbidden) or (4) two pleasure crafts coming together to the port. Figure 2 illustrates these various scenarios.

These types of scenarios cannot be anticipated with usual technologies in MRCCs. Indeed, current surveillance tools do not allow a complete investigation of this situation, for too little analysis tools are available. We remind the definition of complex situation [42], in which the relation between causes and effects requires cannot be anticipated and is only perceived afterwards. In this context, parallel trajectories are complex situation, for their interpretation cannot be anticipated by current surveillance tools, but only with further investigation. Some information can be identified for characterizing these four scenarios, to decide whether there is a case of pirate attack, rescue, or else. Table 1 presents the information to be visualized in each of these scenarios, in order to recognizing the event currently happening.

As we have described above in this paper, the first stage is to define a Situation object in the ontology. In our example, the controller would have to try different exploration, regarding on the type of threat he wants to validate or invalidate. For instance, we define a Situation for exploring a possible parallel fishing scenario, i.e. two fishing ships having simultaneous fishing activities with parallel trajectories. The following axioms are used with pre-defined objects in the ontology:

- *S_hasUser(Situation, User_Controller)*
- *S_hasTime(Situation, Time_RealTime)*
- *S_hasGoal(Situation, G_FishingBehaviorAnalysis)*
- *S_hasRisk(Situation, R_IllegalFishing)*

TABLE I. INFORMATION FOR RECOGNIZING THREATS AND BEHAVIORS IN PARALLEL TRAJECTORIES

Threat	Criteria	Data source
Scenario 1 A being attacked by pirates B	**A:** AIS, **B:** no AIS	AIS, RADAR
	A&B: zigzag trajectory	Rate of turn
	Calm sea	Meteorology
Scenario 2 A being rescued by ship B	No zigzag trajectory	Rate of turn
	A: stopped	Speed & Stops
	A&B: change of heading	Heading
Scenario 3 Parallel fishing	Calm sea	Meteorology
	Speed ~5kn	Speed
	Fishing vessels	Ship type (AIS)
Scenario 4 Pleasure navigation	Same port of origin	Trajectory
	Pleasure craft	Ship type (AIS)

Once the new situation object is added to the ontology, the reasoner analyzes the axioms and applies the rules that are defined. As the goal *FishingBehaviorAnalysis* is already defined, as the process in Fig. 3, the tasks are added to the situation as follows:

- *S_hasTask(Situation, T_GetDirectionChange)*
- *S_hasTask(Situation, T_GetSpeedChange)*
- *S_hasTask(Situation, T_GetStops)*
- *S_hasTask(Situation, T_MeasureSpeed)*

From these inputs, the user profile being defined with his skills, the reasoner ends up with a few visualization spaces adequate to this analysis: *SpeedGraph*, *RateOfTurnGraph*, *TrajectoryMap*, *StopMap* and *SpeedMap*. A geovisual analytics environment could therefore combine these various spaces for visualizing and analyzing the information, such as it is illustrated on Fig. 3 with a single ship. On this example, we use a speed graph, a speed map (color of trajectory), a stop map (proportional circles) and extra information about the ship. With this combination of visualization, we can see that the ship is making important change of heading and stopping on these locations, and is having a mean speed of 4 knots. It is a usual behavior for a fishing vessel, and there is no need for further exploration. With this type of geovisualization, there is less ambiguity regarding the behavior of ships, enhancing resilient situation awareness in maritime traffic.

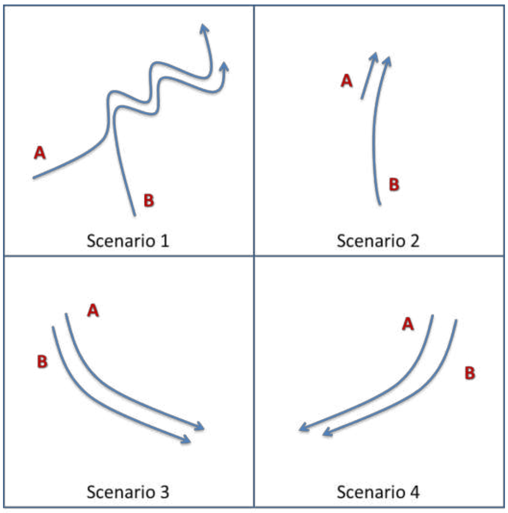

Fig. 2. Parallel trajectories of ships A and B.

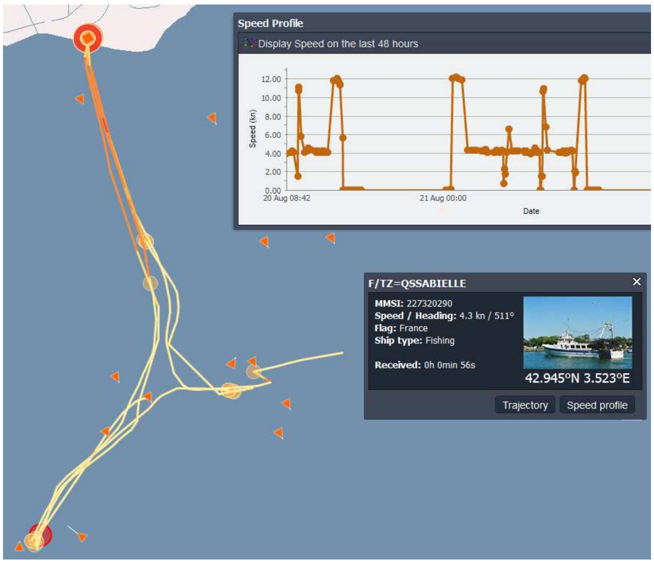

Fig. 3. Geovisual environment for analyzing and validating an on-going fishing behavior.

The same process can be applied to test any other scenario in Table 1, by changing the Goal in the starting situation. New tasks and data for leading this new analysis would be introduced in the reasoning process, thus leading to a new proposition of visualization spaces. From this new environment, the user could lead a new analysis based on his own knowledge and interpretation of the visualized information. This exchange between the knowledge-based system and the human operator allows discovering possible links between the visualized data, which may not have been perceived with usual surveillance tools.

V. CONCLUSION

We have described a framework for supporting the visual analysis of mobility information, in the domain of maritime domain awareness. This support between human operator and computer technologies is based on the formalization of knowledge in geovisual analytics and its contribution to risk assessment for MDA. Ontologies are used for modeling knowledge in geovisual analytics, modeling MDA knowledge with known dangerous patterns, and modeling the analysis process of ships behavior. From this conceptual model, we developed rules to analyze the context of use for geovisual analytics in MDA, and adequate visualization methods according to the data, the tasks and the user profile.

Using adequate visualizations with the support of such a problem solving environment allows human stakeholders in maritime surveillance system to lead improved analysis if the situation, and to trust the results better than automatic identification of the risks. While automatic technologies enable automated alerts in maritime traffic monitoring, visualization allows the user to lead an equivalent analysis of the data. This way, discovery of such results, or validation of automatic alerts are permitted.

Visual environments for such exploration and analysis of the information takes more time than full automation of the process, but it ends up in enhanced confidence and better decision-making. However, it is important to keep in mind that both visual methods and automatic reasoning should not be separated, but complete each other in joint cognitive systems. For instance, results coming from data-mining knowledge discovery could be re-used, once visualization allowed verifying these ones.

Improving the analysis process constantly led by human operators, with the support of intelligent computation and knowledge discovery, shows great result in the detection and the identification of risks while facing major crisis. Hence, there is less ambiguity in searching for threats in current maritime information, and this leaves more time for decision-making with collaboration of many stakeholders. To this end, our proposed methodology for supporting the use of geovisual analytics constitutes one more step towards improving the resilience of maritime domain awareness.

REFERENCES

[1] ICC Commercial Crime Services, “Piracy at sea falls to lowest level in seven years, reports IMB,” 17-Oct-2013. [Online]. Available: http://www.icc-ccs.org/news/873-piracy-at-sea-falls-to-lowest-level-in-seven-years-reports-imb. [Accessed: 27-Feb-2014].

[2] P. van de Laar, J. Tretmans, and M. Borth, Eds., *Situation Awareness with Systems of Systems*. New York: Springer, 2013.

[3] X. Chaze, A. Bouejla, F. Guarnieri, and A. Napoli, “Causal Probabilistic Modeling with Bayesian Networks to Combat the Risk of Piracy Against Offshore Oil Platforms,” *The Radio Science Bulletin*, vol. 345, no. Disaster Management special issue, Jun. 2013.

[4] C. Ray, A. Grancher, R. Thibaud, and L. Etienne, “Spatio-temporal rule-based analysis of maritime traffic,” in *Conference on Ocean & Coastal Observation (OCOSS 2013)*, Nice, France, 2013.

[5] M. Morel and S. Claisse, “Integrated system for interoperable sensors & information sources for common abnormal vessel behaviour detection & collaborative identification of threat (I2C),” *IEEE Conference Publishing*, Piscataway, USA, 2010.

[6] M. Glandrup, “Improving Situation Awareness in the Maritime Domain,” in *Situation Awareness with Systems of Systems*, P. van de Laar, J. Tretmans, and M. Borth, Eds. New York: Springer, 2013.

[7] E. Hollnagel, J. Pariès, D. Woods, and J. Wreathall, *Resilience Engineering in Practice: A Guidebook*. Ashgate Publishing Limited, 2010.

[8] G. Vatin and A. Napoli, “Toward user-centred geovisual analytics in maritime surveillance,” in *GeoViz 2013*, Hamburg, Germany, 2013.

[9] J. W. Reich, A. J. Zautra, and J. S. Hall, *Handbook of Adult Resilience*. New York, NY: Guilford Press, 2010.

[10] A. J. Zautra, “Resilience: A new definition of Health for People and Communities,” in *Handbook of Adult Resilience*, J. W. Reich, A. J. Zautra, and J. S. Hall, Eds. New York, NY: Guilford Press, 2010.

[11] S. S. Luthar, D. Cicchetti, and B. Becker, “The construct of resilience: a critical evaluation and guidelines for future work,” *Child Development*, vol. 71, no. 3, pp. 543–562, Jun. 2000.

[12] A. B. Wildavsky, *Searching for Safety*. Transaction Publishers, 1988.

[13] K. E. Weick, “Improvisation as a mindset for organizational analysis,” *Organization Science*, vol. 9, no. 5, pp. 543–555, 1998.

[14] K. E. Weick and K. M. Sutcliffe, *Managing the Unexpected: Resilient Performance in an Age of Uncertainty*. San Francisco: Jossey-Bass, 2007.

[15] E. Hollnagel, D. D. Woods, and N. Levenson, *Resilience Engineering: Concepts and Precepts*. Ashgate, 2006.

[16] L. K. Comfort, A. Boin, and C. C. Demchak, *Designing Resilience: Preparing for Extreme Events. Pittsburgh*, Pa.: University of Pittsburgh Press, 2010.

[17] D. D. Woods, “Essential characteristics of resilience,” in *Resilience Engineering: Concepts and Precepts*, E. Hollnagel, D. D. Woods, and N. Levenson, Eds. Ashgate, 2006.

[18] M. Davenport and C. Risley, “Information Visualization: the State of the Art for Maritime Domain Awareness,” DTIC Document, 2006.

[19] B. Idiri and A. Napoli, “Towards automatic identification system of maritime risk accidents by rule-based reasoning knowledge,” in *Proceedings of 7th International Conference on System Of Systems Engineering*, Genoa, Italy, 2012.

[20] G. de Vries and M. van Someren, “Recognizing Vessel Movements from Historical Data,” in Situation Awareness with Systems of Systems, P. van de Laar, J. Tretmans, and M. Borth, Eds. New York: Springer, 2013, pp. 105–118.

[21] F. M. Maggi, A. J. Mooij, and W. M. P. van der Aalst, “Analyzing Vessel Behavior Using Process Mining,” in *Situation Awareness with Systems of Systems*, P. van de Laar, J. Tretmans, and M. Borth, Eds. New York: Springer, 2013, pp. 133–148.

[22] A. Vandecasteele and A. Napoli, “Spatial ontologies for detecting abnormal maritime behaviour,” in *OCEANS 2012 MTS/IEEE Yeosu Conference: The Living Ocean and Coast - Diversity of Resources and Sustainable Activities*, Yeosu, South Korea, 2012, pp. 1–7.

[23] J. Roy and M. Davenport, “Categorization of maritime anomalies for notification and alerting purpose,” presented at the *NATO Workshop on Data Fusion and Anomaly Detection for Maritime Situational Awareness*, La Spezia, Italy, 2009.

[24] R. A. Enguehard, R. Devillers, and O. Hoeber, “Comparing interactive and automated mapping systems for supporting fisheries enforcement activities—a case study on vessel monitoring systems (VMS),” *Journal of Coastal Conservation*, vol. 17, no. 1, pp. 105–119, Mar. 2013.

[25] R. A. Enguehard, B. Fowler, O. Hoeber, R. Devillers, and W. Banzhaf, “Integrating human knowledge within a hybrid clustering-classification scheme for detecting patterns within large movement data sets,” in *Proceedings of AGILE 2012*, Avignon, France, 2012.

[26] M. A. Neerincx, S. Kennedie, M. Grootjen, and F. Grootjen, “Modeling the Cognitive Task Load and Performance of Naval Operators,” in *Foundations of Augmented Cognition. Neuroergonomics and Operational Neuroscience*, D. D. Schmorrow, I. V. Estabrooke, and M. Grootjen, Eds. Springer Berlin Heidelberg, 2009, pp. 260–269.

[27] E. Hollnagel and D. D. Woods, *Joint Cognitive Systems: Foundations of Cognitive Systems Engineering*, 1st ed. CRC Press, 2005.

[28] M. Riveiro and G. Falkman, “The role of visualization and interaction in maritime anomaly detection,” in *Proceedings of SPIE-IS&T Electronic Imaging*, San Francisco, CA, USA, 2011, vol. 7868, p. 78680M 1–12.

[29] G. Vatin and A. Napoli, “Guiding the controller in geovisual analytics to improve maritime surveillance,” in Proc. 5th International Conference on Advanced Geographic Information Systems, Applications, and Services (GEOProcessing 2013), Nice, France, 2013, pp. 26–31.

[30] J. J. Thomas and K. A. Cook, *Illuminating the Path: The Research and Development Agenda for Visual Analytics*. National Visualization and Analytics Center, 2005.

[31] A. Dahlbom and T. Helldin, “Supporting threat evaluation through visual analytics,” in *2013 IEEE International Multi-Disciplinary Conference on Cognitive Methods in Situation Awareness and Decision Support (CogSIMA)*, 2013, pp. 155–162.

[32] N. Andrienko and G. Andrienko, “Visual analytics of movement: an overview of methods, tools and procedures,” *Information Visualization*, vol. 12, no. 1, pp. 3–24, 2013.

[33] N. Willems, W. R. van Hage, G. de Vries, J. H. M. Janssens, and V. Malaisé, “An integrated approach for visual analysis of a multisource moving objects knowledge base,” *International Journal of Geographical Information Science*, vol. 24, no. 10, pp. 1543–1558, Oct. 2010.

[34] S. I. Fabrikant, “Building task-ontologies for geovisualization,” presented at the *Pre-Conference Workshop on Geovisualization on the Web*, Beijing, China, 2001.

[35] J. Harding, “Usability of geographic information – Factors identified from qualitative analysis of task-focused user interviews,” *Applied Ergonomics*, 2013.

[36] S. Gallopoulos, E. N. Houstis, and J. R. Rice, “Future research directions in problem solving environments for computational science,” Washington, DC, USA, Apr. 1992.

[37] J. Schiewe, “Geovisualisation and geovisual analytics,” *Kartographische Nachrichten*, no. Special Issue 2013, pp. 122–126, Jun. 2013.

[38] M.-J. Kraak, “Beyond Geovisualization,” *IEEE Computer Graphics and Applications*, vol. 26, no. 4, pp. 6–9, Aug. 2006.

[39] T. R. Gruber, “Toward principles for the design of ontologies used for knowledge sharing,” *International Journal Human-Computer Studies*, vol. 43, pp. 907–928, 1993.

[40] I. Kveladze, M.-J. Kraak, and C. P. J. M. van Elzakker, “A Methodological Framework for Researching the Usability of the Space-Time Cube,” *The Cartographic Journal*, vol. 50, no. 3, pp. 201–210, Aug. 2013.

[41] E. L. Koua and M.-J. Kraak, “Evaluating Self-organizing Maps for Geovisualization,” in *Exploring Geovisualization*, Elsevier Ltd., J. Dykes, A. M. MacEachren, and M.-J. Kraak, Eds. 2005, pp. 627–643.

[42] D. J. Snowden and M. E. Boone, “A Leader’s Framework for Decision Making,” *Harvard Business Review*, vol. 85, no. 11, pp. 68–76.