Visual Analytics for Maritime Domain Awareness

Valérie Lavigne, Denis Gouin
Defence R&D Canada - Valcartier
Québec (QC), Canada

Michael Davenport
Salience Analytics Inc.
Vancouver (BC), Canada

***Abstract*—Maintaining situation awareness in the maritime domain is a challenging mandate. Task analysis activities were conducted to identify where visual analytics science and technology could improve maritime domain awareness and reduce information overload. Three promising opportunities were identified: the visualization of normal maritime behaviour, anomaly detection, and the collaborative analysis of a vessel of interest. In this paper, we describe the result of our user studies along with potential visual analytics solutions and features considered for a maritime analytics prototype.**

Keywords-visual analytics; maritime domain awareness; anomaly detection; situation analysis; collaborative work.

I. Introduction

In this paper, we report on the results of work conducted by Defence R&D Canada (DRDC) in the exploration of Visual Analytics (VA) solutions to real world maritime challenges and describe the design of a Maritime Analytics Prototype (MAP) implementing VA features that will enable better situation understanding. First, we discuss Maritime Domain Awareness (MDA) and its challenges. Results from the task analysis studies identifying VA opportunities are presented, followed by related work. Then, we describe our proposed approach for the MAP along with some of the apps designs for various maritime analysis tasks. We conclude with our plan for future work.

II. Maritime Surveillance

MDA is "the effective understanding of everything on, under, related to, adjacent to or bordering a sea, ocean or other navigable waterway, including all maritime-related activities, infrastructure, people, cargo, and vessels and other conveyances that could impact the security, safety, economy, or environment." [1]

In Canada, the Canadian Forces Regional Joint Operational Centers (RJOCs) in Esquimalt and Halifax maintain a 24/7 watch over Canada's three oceans. The production and exploitation of the Recognized Maritime Picture (RMP) is an essential part of their work. Watch personnel continually interpret the maritime situation with reference to space and time. They need to rapidly process a variety of sources of information in order to develop shared situational awareness. This is a challenging task because of the large number of vessel contacts and heterogeneous information sources that must be monitored. This leads to a significant information overload [2]. Fortunately, VA has emerged as a new and multidisciplinary field that helps turn this information overload into an opportunity.

III. Visual Analytics

Thomas and Cook define VA as "the science of analytical reasoning facilitated by interactive visual interfaces" [3]. The goal of VA is to facilitate high-quality human judgement with a limited investment of the analyst's time. According to them, people use VA tools and techniques to:

- "synthesize information and derive insight from massive, dynamic, ambiguous and often conflicting data;
- detect the expected and discover the unexpected;
- provide timely, defensible, and understandable assessments;
- communicate assessment effectively for action." [3]

VA can help analyze entity behaviour, known patterns, and the links between them.

IV. Maritime Task Analysis

A. *Methodology*

Task analysis activities were conducted to identify the opportunities and potential requirements for the application of VA in the RJOCs.

Our methodology included the review of previous knowledge elicitation studies from related DRDC research projects [4][5]. Then, we organized discussion sessions at the RJOCs in Halifax and Esquimalt. We were also able to observe duty personnel in action in their work environment. The domain knowledge was gathered through a mix of interviews, observations, and group discussions, then documented in a report [6].

B. *Opportunity Identification Results*

The latest requirement elicitation activity identified nine opportunities for applying VA to MDA. This paper summarizes our current R&D activities focused on the first three:

- Visualizing Normal Maritime Behaviour (VNMB)
- Surveillance and Anomaly Detection (SAD)
- Collaborative VA of a Vessel of Interest (CVAV)

We believe that these applications have the highest potential to gain improvement from VA solutions. However, the other opportunities are well documented and could be the basis for future research projects [6].

V. RELATED WORK

A. Visual Analysis of Trajectories

Extensive work on the visual analysis of movement data led to the definition of aggregation methods suitable for movement data and to VA ways to visualize and explore the statistical patterns from trajectories [7]. Interactive Kohonen maps were also used for trajectories aggregation [8].

Clustering of trajectories helps analyze large group behaviours, but it does not easily allow visual identification of anomalous tracks. To this end, [9] produced ship density landscapes in which ships that are off historic routes and regular traffic lanes visually stand out. Vessel movement patterns can also be characterized using hybrid fractal/velocity signatures [10]. As analysts learn to visually interpret these signatures, they can recognize anomalous activities. Innovative tools for geotemporal visualization of trajectories exist [11].

B. Maritime Anomaly Detection

With some exceptions (e.g. [9] and [10]), published work regarding visual detection of anomalies is mostly concerned with network security [12]. The geo-temporal characteristics of vessel trajectory data are very different from computer intrusions, so new strategies are required. Vessel track analysis, for example, is multidimensional and can be affected by factors such as: time of the day/week/year, seasons, meteorological conditions, economic trends, and special events.

When considering maritime anomaly detection specifically, we rapidly find that research has largely focused on developing automated system that suggests potential anomalies to an operator for further investigation. Many of these maritime anomaly detection systems rely on models of normal/abnormal vessel kinetic behaviour to detect anomalies.

Self organizing maps were used and user can be involved in the anomaly detection process using interactive visualizations [12]. Reference [13] uses a Gaussian mixture model for maritime anomaly detection while [14] uses a Bayesian network. Spline-based trajectory clustering techniques were proposed by [15] to represent normal vessel behaviour for coastal surveillance. The use of a neurobiologically inspired algorithm for probabilistic associative learning of vessel motion was suggested by [16].

Rule-based expert systems rely on artificial intelligence rules derived from human expert knowledge acquisition activities. Such a system was built at DRDC [17], which we will use as an input in our prototype. This approach was also employed by [18].

C. Maritime Situation Analysis

Although the geospatial trajectory of a vessel is its most salient signature, maritime situation assessment requires the analysis of more varied data such as port visit history, owner relationships and suspected criminal activities. The advantages of visualization for data mining applications are outlined by [19] and a number of examples are provided. The tight link between VA and data mining is also discussed by [20].

Visual exploration strategies can be used to extract patterns from past behaviour in a dynamic geo-spatial area of interest. For example, the study of Somali pirate attacks [21] shows that the attack pattern changed in response to the creation of the Maritime Security Patrol Area.

To the best of our knowledge, VA techniques have not been used in focused analysis of specific entities in the maritime domain. General trends were often identified but the visual analysis of individuals has received much less attention.

VI. MARITIME ANALYTICS PROTOTYPE

The intent of the Maritime Analytics Prototype (MAP) is to improve the visualization of the recognized maritime picture and help analysts better comprehend a situation and anticipate how it could develop.

A. Mix of Original and Existing Concepts

Our proposed Maritime Analytics Prototype (MAP) is a mixture of original innovative concepts and existing VA and information visualization concepts that are not presently applied to MDA. We may also integrate available academic and commercial VA solutions such as GeoTime [11], JigSaw [22] and nSpace [23].

The contribution of this work is twofold:

- Existing theoretical and applied VA approaches have been extended and assembled into a suite that is optimized for this application.
- New VA innovative concepts have been developed in response to specific maritime domain requirements.

B. Apps Design Approach

Because of their 24/7 operational context, the RJOCs have for many years upgraded their information technology through a series of incremental improvements, rather than through system replacement cycles. Accordingly, the MAP will consist of a set of services that could be added incrementally to a service-oriented architecture. The MAP has thus been designed as a set of compact software applications (apps), with the following characteristics:

- Transient: each app can pop up when needed and then hide away under an icon when not needed.
- Self-contained: apps can be added as a service without requiring changes to the operating system or to other applications.
- Single-purpose: users experience each app as doing one specific job.

DRDC Valcartier and Salience Analytics Inc performed design studies activities that led to 24 apps concepts [24] related to the three selected MDA opportunities. This paper describes a subset of these apps.

C. Workspace and App Icon Collection

There will be a common operational context in which all the apps will operate. The MAP workflow will allow easy movement between different interconnected views of the domain by letting users select, customize, and arrange the views that contribute to their current task, effectively providing a user-defined operational picture [25]. Commonly-used arrangements can be saved and deployed. Automatically configured layouts based on the user role will also be provided.

Portal views may be stacked on a single screen, distributed across multiple screens, or distributed between devices such as a laptop, a wall display or a tablet (Fig. 1). Views generated externally (e.g. a video feed of the harbour) can also share the workspace.

Figure 1. Multiplatform Maritime Analytics Prototype mock-up.

VII. Visualizing Normal Maritime Behaviour

The goal of VNMB is to use VA to produce and record a description of what is normal in an area of interest. The available knowledge about maritime behaviours, trends and patterns is largely built up from individual analyst's experience and mentoring from more experienced analysts. Once patterns are identified, pictures and annotations could be used to visually display this knowledge. The normal pattern of life would then be more easily transmitted to new analysts.

Various elements of information are of interest to help understand normal maritime behaviour such as historical commercial routes and fishing areas. Analysts must also understand how external factors, such as seasonal activities, meteorological conditions and economic influences affect the maritime activities or sensor performance.

A. *Bubble Sets for Fleets*

Exploration of the dataset is critical to support the analytical process and develop insight. The number of tracks that can be displayed in the RMP is overwhelming. Just as contact data have been resolved into tracks, tracks should be clustered into groups in order to reduce visual clutter. The whole maritime dataset can then be explored one set at the time, while maintaining the possibility to drill down and look at individual vessels at anytime.

Creating groups of tracks can be done using automatic or manual selection. Allowing queries to plot all tracks that meet specified criteria (such as time windows, spatial zones, ship sizes, destinations, range of headings) will enable the analyst to filter the dataset. A number of tracks can then be selected to manually create a new set. Various automatic clustering algorithms were mentioned in the Related Work section.

Because vessel icons are set by a military standard, we need an alternative to color coding to show set membership. Bubble sets [26] can group many entities visually into a single blob without affecting their spatial organization. Considering the shape of these blobs can even allow additional analysis capabilities. Any ship that is far away from the other members of the group will become salient as the blob shape stretches in its direction. This shape could become a feature that can be easily recognized for known fleets and any change would hence be easily noticed. Fig. 2 shows a bubble set used in conjunction with thematic views.

Figure 2. Bubble sets and thematic views.

B. *Thematic Views*

In order to reduce information overload, we need to allow users to focus on the specific subsets of information required for their current task. In the thematic views app, visual layers separate the information elements into various themes such as commercial transportation, Vessels of Interest (VOIs) surveillance, sensor coverage analysis, or alerts from automatic anomaly detection systems. The possibility to hide or show individual layers of information allows the user to view only the relevant information needed for a particular task.

Various combinations of visualizations can be proposed. We can create generic layouts for tasks or topics that are common and recurrent, as well as allowing users to create their own custom visual layouts employing the tools that suit their needs. An example of this would be to display together fishing vessels, regulatory fishing zones, meteorological data and some annotations from a previous normal behaviour analysis (Fig. 2). A visualization of tracks on the map along with the boundaries of a region of interest allows direct assessment of their relative position. This could be useful, for instance, to see if fishing ships are actually in fishing zones or to detect ships that have failed to provide their 24 hr or 96 hr call-in reports.

VIII. Surveillance and Anomaly Detection

An important goal of surveillance is to detect anomalies in the current situation. A huge fraction of the information presented to RJOC operators is mundane, from entities going about normal, legitimate activities. As a result, important anomaly information can be masked by the sheer volume of data.

One approach often considered is automatic anomaly detection. To this end, a DRDC project [17], has successfully explored the use of rule-based and description logic expert systems. Validation of alerts still needs to be done by human analysts. There are some anomalies however, either difficult to describe in a formal language or simply unexpected, that the automated rules will miss.

In contrast, VA detection of anomalies takes full advantage of the human ability to explore, create hypotheses and analyze what is going on. The computational strength of the machine is exploited in another way through the use of clever visualization, automatic clustering, and interactive analytical algorithms.

Anomaly detection is closely related to VNMB because an analyst needs to know what is normal to detect what is not. Patterns identified in VNMB can be visually compared to the current situation, or can be used to suppress mundane data, so that anomalies stand out. Even though we will leverage automated reasoning for anomaly detection from previous activities [17], the MAP focuses on innovative visual apps that help the operator detect unexpected anomalies by exploring the maritime situation.

A. Close-Encounters Pop-Ups

If we consider the situation where an analyst wants to check if a rendezvous has taken place, the visualization of tracks on a map does not allow this fact to be verified rapidly. The operator would need to use a time slider and replay the scene or turn on the time labels for each contact and mentally compare them.

The proposed encounter icon in Fig. 3 gives a temporal overview for the narrow vicinity of a specific vessel. The icon is centered on the frame of reference of the current ship. A simple way to picture this concept is to imagine the icon moving along the ship track while other vessels leave a trace in it as they cross it. This pictogram tells the operator instantaneously if any other vessel has been in proximity to this ship anywhere during its complete journey.

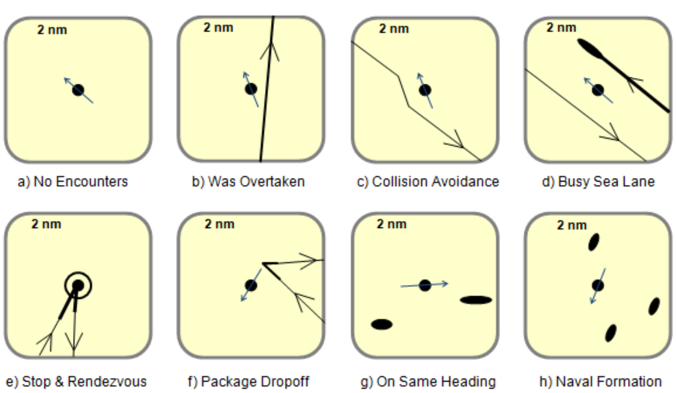

Figure 3. Examples of close-encounter pop-up icons.

The close-encounters icons can pop-up when we do a mouse-over on the tracks and instantly reveal if meetings may have happened. It can also be included in a vessel summary card. For wide-area surveillance, a single button will create pop-ups for all tracks of interest, so that a quick check can be done for all tracks (Fig. 4).

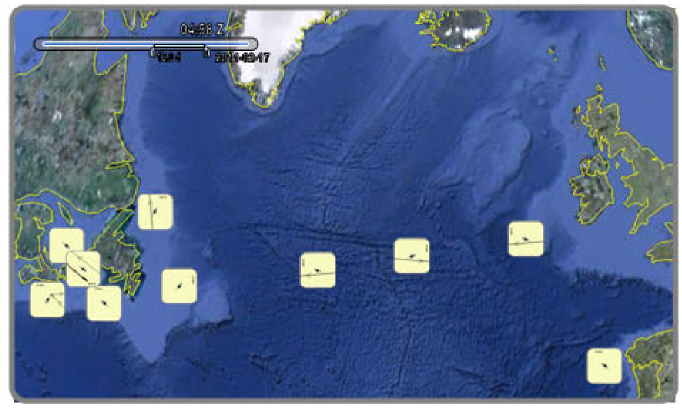

Figure 4. Close encounter pop-up icons on the map.

B. Vessel Summary Cards

The information elements related to an individual vessel may be of different natures (e.g. tracks on maps, crew and passenger lists, flag, photographs, spreadsheets of financial transactions, schedules, textual documents). Visual representations of these information bits can be assembled to create a visual vessel summary as shown in Fig. 5.

The vessel summary cards show all the key characteristics of a vessel at a single glance and analysts can rapidly flip through a virtual deck of summary cards. Information is formatted so that the analyst can look for normally present or absent elements rather than having to read each card. The cards are updated for each vessel journey and previous versions are accessible. Details are available on demand by clicking the corresponding visual element.

Figure 5. Tablet browser for visual vessel summary cards.

C. Route Ribbons

Transcontinental ships follow predictable routes, and any deviation from those routes is noteworthy. Route ribbons visually represent deviation from travel plans, as sketched in Fig. 6. The current track is displayed as a line. The space between this line and the expected route is filled with color, creating the "ribbon". The ribbon gets larger as the vessel deviates from its normal route, thus increasing saliency as the behaviour becomes anomalous. An analyst can pop-up a temporary route ribbons overlay to get an instant visual indication of how well transcontinental ships are staying on great circle routes. The ribbons also show if vessels are not heading to their stated destination

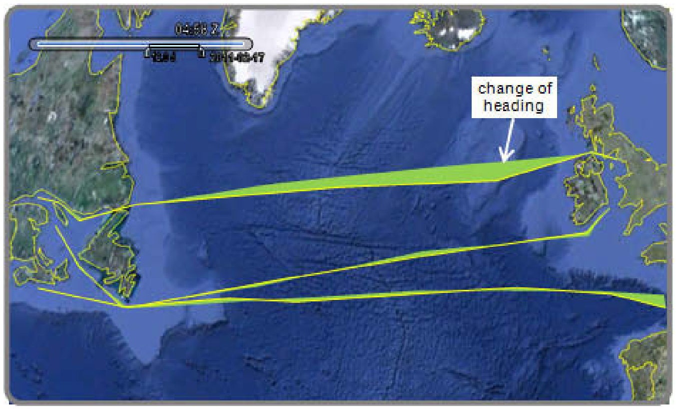

Figure 6. Route ribbon example.

IX. COLLABORATIVE ANALYSIS OF A VESSEL OF INTEREST

The RJOCs and MSOC agencies do not have enough manpower to fully analyze and interpret every vessel in Canada's area of responsibility so they use triage to identify Vessels of Interest (VOIs) that are worthy of special attention.

Once a VOI has been declared, multiple agencies and individuals collaborate to collect, interpret, and disseminate as much information as possible about the vessel. Within Canada, six federal departments are involved as part of the Maritime Security Operation Center (MSOC).

Detailed analysis of a VOI is necessary to understand the intentions of the ship and whether it may represent a threat. To this end, the information that need to be visualized is a mixture of ship tracks, photographs, schedules, self-reported information, commercial facts, and intelligence information.

A. Mind Map with Time Slider

Commercial VA solutions such as GeoTime [11] have demonstrated the value of a tool in which observations can be collected, hypotheses tested, and a story constructed to interpret the evidence.

Our prototype will incorporate such a Mind Map app and will assess the value of explicitly visualizing the time evolution of the analytical story being told. As with other such tools, users can drag and drop into the Mind Map new evidence or snapshots of the current maritime picture. When reviewing the evidence, analysts can choose to display the nodes and links on a timeline (see Fig. 7) to provide the temporal context (past and future elements are faded). Expected or planned events (e.g. the departure of a ship) can also be placed in the future of the Mind Map App.

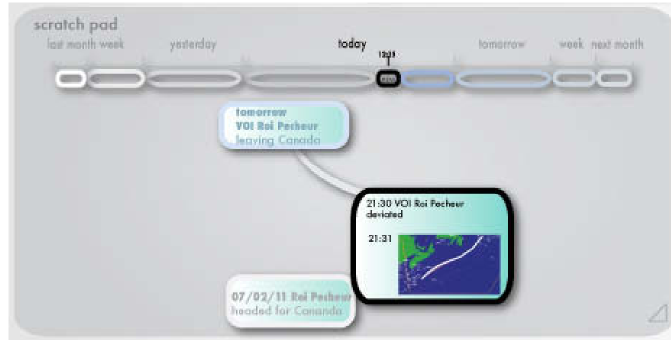

Figure 7. Mind map with time slider.

By explicitly showing this temporal evolution, we expect that analysts will have better insight into the reasons for past decisions, and will thus be more empowered to correct mistakes when they are discovered. The temporal tagging of all the information makes it easier to later explain the thought process that led to the conclusions presented in reports, helping decision tracking and auditing. It will only be useful, however, if Mind Map data can be collected using a mechanism that requires so little time and energy that operators do not perceive it as an added drain on their time.

B. Predictive Rendezvous

Fig. 8 shows a simple app for quickly visualizing when and where a rendezvous or interception might occur, given sparse tracking information. In this example the analyst suspects two ships of planning to intercept and harass an oil tanker. The time slider at the top left is adjusted to explore a potential intercept time and the app shows:

- Where the tanker would be at the specified time,
- How close the two attacking ships could be at that time, if travelling at top speed, and
- When an aircraft would have to leave the nearest airbase, to arrive on-scene at that time.

A key element of this App is the real-time re-mapping of the scenario as the time slider is adjusted. This provides a dynamic visual component that summarizes a complex what-if decision space. The colored time slider also indicates the interval in which the vessel trajectories intercept.

Figure 8. Predictive rendezvous analysis.

C. *Enabling Collaboration*

The VA prototype will be tested in a physical collaborative environment that combines individual workstations, large group displays, and network infrastructures with collaboration services such as conferencing. A multi-touch table will be used as a shared workspace where information from different departments can be brought together to discuss a VOI situation. We expect this advanced collaborative environment to improve the collaboration of co-located and virtual teams. We favour use a web based approach, leading to easier multi-device use.

X. Conclusion

In this paper, we identified a subset of maritime applications and tasks where the use of VA has a high improvement potential and focused on improving the visualization of normal maritime behaviour, the detection of anomalies and the collaborative analysis of a VOI.

The VA solutions we propose will offer cognitively rich visual representations that will lead to a more efficient exploration and analysis of the current maritime situation. These tools will also support communication of analysis results and teamwork collaboration. With our apps-based design approach, we propose new innovative VA capabilities and apply existing VA concepts to a real world problem.

Although all the proposed apps are tailored to address specific cognitive overloads that have been identified by RJOC personnel, the operational value of each app cannot be assessed until the prototype has been built and controlled evaluations done.

Our future work will focus on implementing the maritime analytics proof-of-concept prototype. User validation and evaluation activities will be conducted. They will provide an opportunity to integrate user suggestions and preferences into future versions. Advancement regarding the VA prototype will be described and discussed further in subsequent papers.

References

[1] National Security Presidential Directive/Homeland Security Presidential Directive, Maritime Security Policy, NSPD-41/HSPD-13, 2004.

[2] W.M. Renaud and A.W. Isenor, “Situational Awareness: Inspiring Operational Clarity”, Canadian Military Journal, 10 (4), 2009.

[3] J.J. Thomas and K.A. Cook, eds., “Illuminating the Path: The Research and Development Agenda for Visual Analytics”, IEEE Computer Society Press, 2005.

[4] M. Davenport and S. Franklin, “Visions of a Future Maritime Picture”, MacDonald Dettwiler and Associates Ltd., DRDC Scientific Authority: David M. F. Chapman, DRDC Atlantic CR 2006-038, May 2006.

[5] M. Davenport, “Maritime Domain Awareness Knowledge Management Requirements”, MacDonald Dettwiler and Associates Ltd., DRDC Scientific Authority: Jean Roy, DRDC Valcartier CR 2007-174, July 2007.

[6] M. Davenport, “Opportunities for Applying Visual Analytics for Maritime Awareness”, MacDonald Dettwiler and Associates Ltd. & Salience Analytics, DRDC Scientific Authority: Valérie Lavigne, DRDC Valcartier CR 2009-227, October 2009.

[7] G. Andrienko and N. Andrienko, “Spatio-temporal Aggregation for Visual Analysis of Movements”, Proc. of the IEEE Symposium on Visual Analytics Science and Technology 2008 (VAST 2008), pp. 51-58.

[8] T. Schreck, J. Bernard, T. Tekusová and J. Kohlhammer, “Visual Cluster Analysis of Trajectory Data with Interactive Kohonen Maps”, Proc of the IEEE Symposium on Visual Analytics Science and Technology 2008 (VAST 2008), pp. 3-10.

[9] N. Willems, H. van de Wetering and J.J. van Wijk, “Visualization of Vessel Movements, Computer Graphics Forum”, In Proc. of EuroVis 2009, 28(3), p.959-966.

[10] R.A. Enguehard, R. Devillers and O. Hoeber, “Geovisualization of Fishing Vessel Movement Patterns Using Hybrid Fractal/Velocity Signatures”, GeoViz Workshop, 2011.

[11] T. Kapler, R. Eccles, R. Harper and W. Wright, “Configurable Spaces: Temporal Analysis in Diagrammatic Contexts”, IEEE Visual Analytics Science and Technology (VAST 2008), October 19-24, 2008, Columbus, Ohio, USA.

[12] M. Riveiro, G. Falkman and T. Ziemke, “Visual Analytics for the Detection of Anomalous Maritime Behavior”, IEEE 12th International Conference Information Visualisation, 2008.

[13] R. Laxhammar, 2008. “Anomaly Detection for Sea Surveillance”, Proc. of the 11th International Conference on Information Fusion (Fusion 2008), 47–54, (June-July 2008).

[14] F. Johansson and G. Falkman, “Detection of Vessel Anomalies - a Bayesian Network Approach”, Proc of the 3rd International Conference on Intelligent Sensors, Sensor Networks and Information Processing, 2007.

[15] A. Dahlbom and L. Niklasson, “Trajectory Clustering for Coastal Surveillance”, Proc of the 10th International Conference on Information Fusion (Fusion 2007), July 2007.

[16] B.J. Rhodes, N.A. Bomberger and M. Zandipour, “Probabilistic Associative Learning of Vessel Motion Patterns at Multiple Spatial Scales for Maritime Situation Awareness”, Proc of the 10th International Conference on Information Fusion (Fusion 2007), July 2007.

[17] J. Roy, “Rule-Based Expert System for Maritime Anomaly Detection”, Proc. of the 12th International Conference on Information Fusion (Fusion 2009), July 2009.

[18] J. Edlund, M. Grönkvist, A. Lingvall and E. Sviestins, “Rule Based Situation Assessment for Sea-Surveillance”, Proc of SPIE -Multisensor, Multisource Information Fusion: Architectures, Algorithms and Applications, vol. 6242, 2006.

[19] D.A. Keim, “Information Visualization and Visual Data Mining”, IEEE Transactions on Visualization and Computer Graphics, 7 (1), 2002.

[20] A. Perer, and B. Shneiderman, “Integrating Statistics and Visualization for Exploratory Power: From Long-Term Case Studies to Design Guidelines”, IEEE CGA, pp. 39-51, 2009.

[21] UNOSAT, “Pirate Attack Density in the Gulf of Aden”, Product ID: 1298 – English, 26 Nov, 2008.

[22] J. Stasko, G. Carsten and L. Zhicheng, “Jigsaw: Supporting Investigative Analysis through Interactive Visualization”, Information Visualization, 7(2), p.118-132, 2008.

[23] W. Wright, D. Schroh, P. Proulx, A. Skaburskis and B. Cort, “The Sandbox for Analysis - Concepts and Methods”, ACM CHI, 2006.

[24] M. Davenport, V. Lavigne and D. Gouin, “Design of a Maritime Domain Awareness Visual Analytics Prototype (DMVAP), Task 1: Design Study”, Salience Analytics, DRDC Scientific Authority: Valérie Lavigne, DRDC Valcartier CR 2011-221, July 2011.

[25] S. Mulgund and S. Landsman, “User Defined Operational Pictures for Tailored Situation Awareness”, in the Proc of the 12th International Command and Control Research and Technology Symposium - Adapting C2 to the 21st Century, Newport, RI, June 19-21, 2007.

[26] C. Collins, P. Gerald and S. Carpendale, “Bubble Sets: Revealing Set Relations with Isocontours over Existing Visualizations”, IEEE Transactions on Visualization and Computer Graphics (Proc. of the IEEE Conf. on Information Visualization), 15 (6), Nov/Dec 2009.