Interactive Visualization Applications for Maritime Anomaly Detection and Analysis

Valérie Lavigne
Defence R&D Canada
2459 PIE-XI Nord, Bat 24
Québec, Qc, Canada, G3J 1X5
Tel: 1 (418) 844-4000
valerie.lavigne@drdc-rddc.gc.ca

ABSTRACT

A study of maritime surveillance operations revealed that visual analytics could enable better maritime situation analysis. For that purpose, we designed the Maritime Visual Analytics Prototype, which is detailed in this demo paper. It supports the detection of marine anomalies and the detailed analysis of vessels of interest through a series of specialized tools. First, the Analysis Set Manager acts as the central repository and starting point for tools launching. The Animated Map and Timeline enable visual anomaly detection related to vessel tracks using Route Ribbons and Close Encounter Icon visualizations added to an interactive geo-temporal display. The Visual Summary Cards presented in the Record Browser display the key vessel characteristics for rapid visual scanning. The Magnets Grid enables a multi-dimensional exploration of factual vessel information, while temporal analysis is performed using the Multi-Timelines. This prototype was tested with operational maritime surveillance data and evaluated through user jury trials with real potential users. Comments from the users indicate that the visual widgets proposed could be valuable to their daily operations.

Categories and Subject Descriptors

H.5.2 [**Information Interfaces and Presentation**]: User Interfaces – *graphical user interfaces (GUI), user-centered design.*

General Terms

Management, Design, Experimentation, Security, Human Factors.

Keywords

Visual analytics, anomaly detection, situation analysis, maritime domain awareness, user jury validation.

1. INTRODUCTION

Maritime domain awareness is defined as "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, ensuring coastal safety by detecting marine threats in a sea of vessel track data falls within the responsibility of the Coastal Marine Security Operation Centres (MSOC), where the staffs gather and analyze information, and produce specialized intelligence products to support operational decision makers during routine and contingency operations [2]. This mandate exceeds awareness and involves focused analysis. To build and maintain a shared understanding of the maritime situation is very challenging and can lead to significant cognitive overload. Visual Analytics (VA) technologies could be beneficial to that endeavor.

In this paper, we present a study of VA applied to maritime domain challenges, including the requirements identified for a maritime VA tool suite, the Maritime Visual Analytics Prototype (MVAP) that we designed and implemented, and the results of the validation activity that followed.

1.1 Application of Visual Analytics for Maritime Domain Analysis

In this project, we conducted a detailed study investigating how VA can benefit maritime domain analysis. We first performed multiple knowledge elicitation sessions to identify important challenges and visual requirements related to maritime domain analysis. We decided to focus our research on the two following tasks: maritime anomaly detection and vessel of interest analysis. In our design, we split the visualization needs into a series of VA tools using a modular approach. That led to the development of the MVAP which is the subject of this paper.

1.2 Validation with Target Users

The MVAP was evaluated by real potential users from each of the five federal departments involved in the MSOCs and representing a variety of maritime security functions. A hands-on group training session was followed by a series of individual tasks to perform. The MVAP and the tools that comprise it were assessed using Standard Usability Scale surveys, user rankings of individual tools, observations and interviews. Moreover, the MVAP was tested with real surveillance data which contributed to showing the users its operational potential.

Validation results and comments from the users indicate that the visual widgets proposed could indeed be valuable to their daily operations. This activity also generated insights useful for VA tool design and assessment.
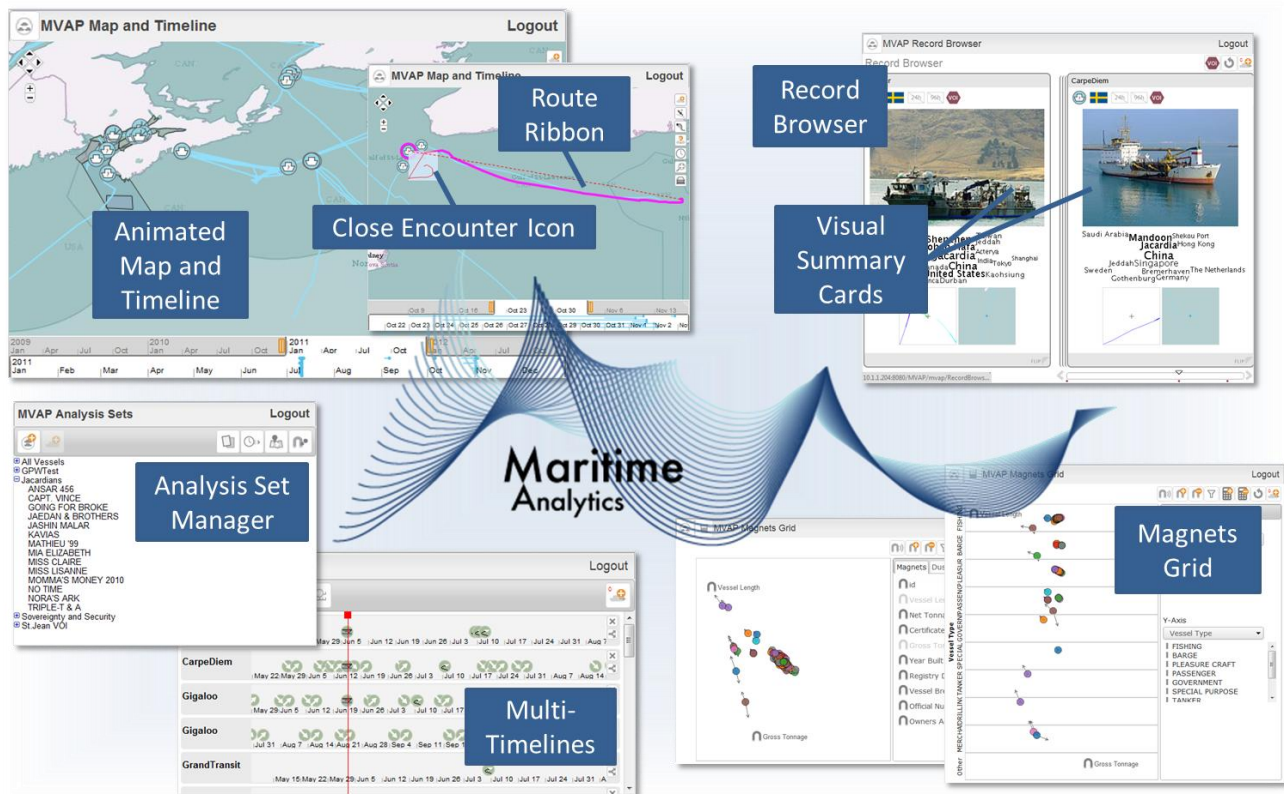
Figure 1. This is an overview of the Maritime Visual Analytics Prototype tools for visual marine threat identification and analysis.

2. REQUIREMENTS ANALYSIS

"The MSOCs provide comprehensive marine domain awareness along Canada's coasts enabling detection, assessment, and response to threats that could adversely affect the safety, security, environment or economy of Canada. Threats include foreign trans-national organized crime - drug trafficking, piracy, migrant smuggling - emerging terrorist activity, over-fishing, and polluters" [2]. To do that, the MSOCs perform a 24/7 watch over Canada's three oceans. Heterogeneous sources provide information related to the thousands of vessels that can cross their area of responsibility.

After a review of previous knowledge elicitation studies from related DRDC research projects [3, 4], we conducted requirements analysis sessions with interagency civilian and military staff involved in the MSOCs. 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. We identified a series of tasks that could benefit from VA tools [5], but chose to focus our limited research resources on the two activities which presented the highest improvement potential from the VA science and technology: identifying anomalies related to vessel tracks and information, and performing a focused analysis of a situation that involves a vessel of interest.

2.1 Anomaly Detection

The MSOCs do not have enough manpower to conduct a full analysis of every vessel in their areas of responsibility, so they use triage to identify vessels that may present a threat and require detailed analysis. Unfortunately, vessels with anomalous behaviours or suspicious connections are not easily detected

among the very large number of vessels going about normal, legitimate activities.

They need the ability to recognize outliers that do not behave as expected as well as the ability to spot individuals who behave in a way similar to previously identified threats.

2.2 Vessel of Interest Analysis

Vessels of Interest (VOIs) are those vessels that require special attention. They are not declared lightly and a procedure must be followed. When a vessel is designated as a VOI, a number of people will gather information and conduct detailed analysis in order to make a judgment about the case. This detailed analysis can also lead to the identification of other potentially interesting individuals.

2.3 Information to Represent

To detect maritime anomalies and to represent what can be known about a VOI, three main categories of information must be considered [5]:

• Geo-temporal: mainly the vessel's track, including related data such as speed

• Temporal: significant events involving the vessel

• Factual: known information elements about the vessel, related people or organizations, and physical properties.

2.4 Other Considerations

Additionally, we must consider the constraints that come from working in a defence and security environment like the MSOCs. Frequent staff changes are expected and the time that can be devoted to training is very limited. Thus, the proposed tools should be easy to learn and provide an intuitive interface.

The Canadian Charter of Rights and Freedoms, and the Privacy Act must be taken into account when collecting, using and sharing information. For that reason, the data that different governmental agencies collect are not shared directly in a common data repository. Tools should allow users to import/export the data from/to different formats to facilitate sharing when working on a case with other agencies.

3. LITERATURE REVIEW

3.1 Anomaly Detection

3.1.1 Automated Detection

In the maritime domain, many researchers attempted to detect anomalous vessel behaviours automatically relying on models of normal/abnormal vessel kinetic behaviour.

Laxhammar [6] uses a Gaussian mixture model for maritime anomaly detection while Johansson and Falkman [7] use a Bayesian network. Spline-based trajectory clustering techniques were proposed by Dahlbom and Niklasson [8] to represent normal vessel behaviour for coastal surveillance. Rhodes et al [9, 10] suggest the use of a neurobiologically inspired algorithm for probabilistic associative learning of vessel motion.

Riveiro et al [11, 12] opt for self-organizing maps but allow user involvement in the anomaly detection by providing interactive visualizations and a data mining module that supports the insertion of the user's knowledge and experience.

An automated approach for anomalous vessel behaviour detection was also researched at DRDC, employing a rule-based expert system which allowed an operator to express anomaly rules that take advantage of both kinetic and non-kinematic vessel properties [13]. A similar approach was also employed by Edlund et al [14].

These automated approaches produce very good results for suspicious patterns that were previously noticed and can be clearly expressed. However, they do not allow for first time discovery of new patterns, so a visual anomaly detection approach could very well complement automated systems.

3.1.2 Visual Detection

Extensive work can be found regarding the visual analysis of trajectories, but they often focus on identifying larger trends in the data, not in detecting outliers.

Willems et al [15] produced ship density landscapes in which ships off historic routes and regular traffic lanes visually stand out. Vessel movement patterns can also be characterized using hybrid fractal/velocity signatures [16] to recognize anomalous activities. TripVista [17] offers spatial, temporal and multiple-dimensional perspectives to analyze micro terrestrial traffic data for finding regular patterns and anomalies of traffic flows. These projects address several types of trajectory anomalies but ignore abnormal situations that can be detected using non-kinetic data.

Most of the VA literature concerning anomaly detection is concerned with network security and the techniques employed are not easily transferable to the maritime domain where the geo-temporal aspect is a central analysis component.

3.2 Vessel of Interest Analysis

Multi-dimensional visualization of aspects of the traffic trajectory data with parallel coordinates plot was proposed in TripVista [17]

and [18] (adding physical ship properties). As for anomaly detection, the focus of current research remains on trajectory data. Although the geospatial trajectory of a vessel is the most salient signature, maritime situation assessment requires the analysis of more varied data such as port visit history, owner relationships and suspected criminal activities.

Not focusing specifically on maritime situations, Keim [19] outlines the advantages of visualization for data mining applications and gives a long list of examples. Perer and Shneiderman [20] also discuss the tight link between VA and data mining. Although visual data mining often helps identifying global trends, the visual analysis of individual entities has received much less attention.

4. THE MARITIME VISUAL ANALYTICS PROTOTYPE

The MVAP was developed to explore the potential of VA techniques for visual anomaly detection and situation analysis in the maritime domain.

4.1 Our Approach

Early in our design process, we decided to adopt a modular approach, where each of the proposed tools would be independent and focus on a specific analysis perspective. We designed a series of concepts [21], presented them to potential users and selected the most promising ones to be included in MVAP.

The map rapidly appeared as the natural choice for representing the vessel track information, with an important focus on combining the geographical and temporal aspects together. We added a few innovative concepts in an attempt to make some types of trajectory anomalies more salient. As temporal information is very important for pattern detection, we created a specialized widget that focusses on temporal patterns detection. Factual information exploration was divided between multi-dimensional simultaneous exploration and visual summaries for quick scan and comparison.

The strength of splitting the different functionalities across specialized widgets is that it avoids imposing a steep learning curve to a user who only needs a fraction of the MVAP capabilities. We expect simple single purpose tools will also require less training than a complex application offering all these features together. On the other hand, a potential drawback is that it may result in a fractioned analysis where the overall picture is hard to grasp.

This decoupled approach also facilitates the eventual operational deployment of the tools by not imposing a large application to end users who may only be interested in one widget. An added benefit is to facilitate the reuse of some of the tools for other application domains, such as social network analysis in a counter-insurgency context [22].

The prototype interface is implemented in JavaScript and runs in a web browser with a service oriented architecture backend. The following subsections describe the functionalities that each MVAP widget offers. Figure 1 provides an overview of all the MVAP tools.

4.2 Analysis Set Manager

The Analysis Set Manager serves as a central repository for the analysis sets that are built using the other tools of the MVAP. It

features a hierarchical tree of analysis sets listing all the vessels that they contain (Figure 2). With the Analysis Set Manager, the user can organize objects into meaningful analysis groups. For example, a list of vessels that need to be monitored closely could be managed from the Analysis Set Manager. The visual encoding for managing the sets of vessels mimics the use of a file browser, providing a familiar concept to most computer users.
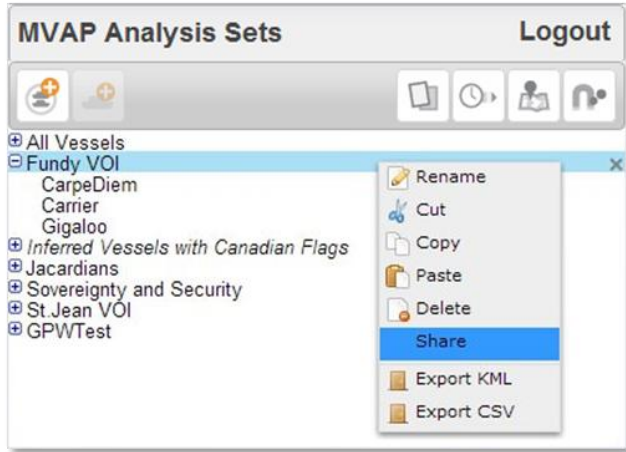

Figure 2. The Analysis Set Manager is the main repository and launching point for the other VA tools. It features a hierarchical display of vessel sets. Sets displayed in italic were generated using artificial reasoning services.

Analysts are not expected to create all the vessels lists manually. Partial automation of the process is performed by taking advantage of artificial reasoning services to automatically create "smart sets" according to predefined rules. This leverages the previous work performed with expert systems that can detect a large number of anomalous situations automatically [13], effectively combining our interactive visualization approach with automated data mining. These smart sets can be regularly updated and are displayed in italic to differentiate them from sets resulting from manual selection or visual analysis.

The Analysis Set Manager is also the launching point for the other VA widgets, which allow operators to identify more anomalies and patterns, as well as to explore the details of the reported anomalies from the data mining process.

4.3 Animated Map and Timeline with Visual Encodings

The use of a geographical map is central to maritime situation analysis. In the MVAP, this essential capability is provided by the Animated Map and Timeline (Figure 3), which add temporal animation to the map visualizations currently available in operational systems. It contains a geographical display with a timeline added below that lets the user select the active time interval for data display. The top part of the timeline contains an overview of the selected time interval and the bottom part is a zoomed in version. The selected interval can be dragged to animate the vessel tracks on the map, in order to perform spatiotemporal analysis

Two innovative visual representations are integrated into the map display: the Close Encounter Icons and the Route Ribbons (Figure 4). Their purpose is to facilitate visual detection of track anomalies, including encounters and vessels not taking the shortest route to their stated destination.
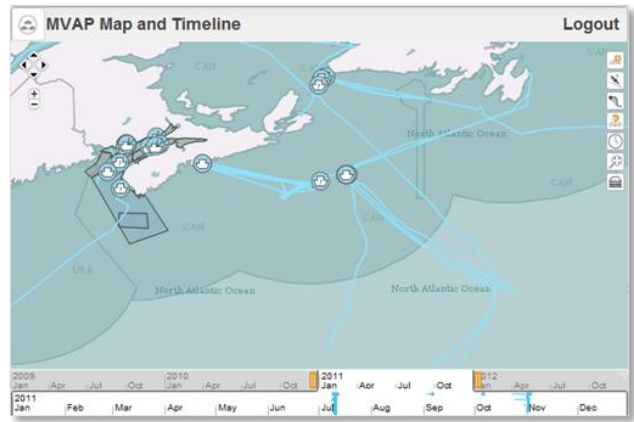

Figure 3. The Animated Map and Timeline offers an interactive display of vessels tracks where the user can select a time interval at the bottom of the interface and drag it to animate the tracks backward or forward.
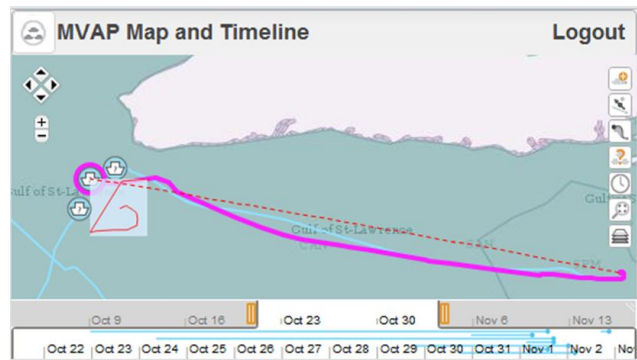

Figure 4. Route Ribbons and Close Encounter Icons appear when a vessel is selected or can be turned on for all vessels. Route Ribbons increase the saliency of vessel tracks following unexpected routes.

A Close Encounter Icon is a square area that is centred on a vessel. This icon follows the vessel during its journey and other vessels that come near it will leave a trace within the icon as they cross it. Figure 5 highlights possible icon patterns that can happen along with their associated meanings. This icon summarizes a vessel's journey and shows in a single glance whether there were close encounters, helping the analysts triage which tracks to animate for further analysis. The Route Ribbons trace a dotted line representing the expected route for the vessel for comparison against the actual track, resulting in increased saliency for anomalous tracks.

The Animated Map and Timeline widget also serves as a spatio-temporal filtering tool for creating meaningful sets of vessels to analyse with the other MVAP tools.
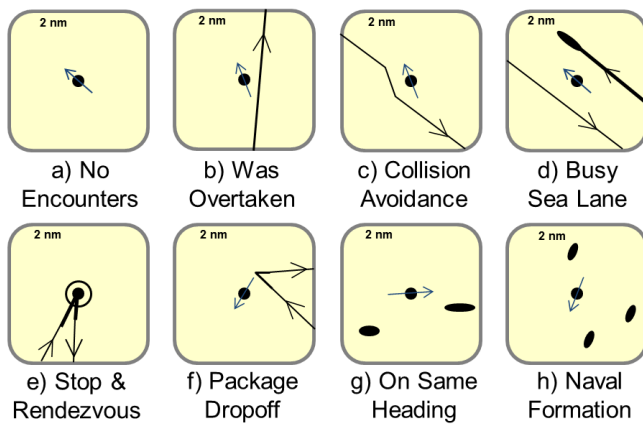
Figure 5. The Close Encounter Icon is a visual representation centered on a vessel and moving with it, where other vessels crossing its path leave a trace inside this square area. Here are a few potential examples with their associated meanings [23].

4.3.1 Modified Version for Handling Real Operational Data

A specialized version of the Animated Map and Timeline widget was created to handle the large amount of tracks present in real data. We ingested a 40 GB operational dataset of 112 million position reports spanning over a year, related to 75 000 vessels.

A benefit of creating this widget version is that it contributed to gaining credibility in the eyes of the target users and getting their attention. Real data also tested the limits of the system with regards to dealing with large datasets.

A few features were added to that version, extending its capabilities with automatic detection of loiterers and vessel encounters within a selected region and time. This detection preprocessing and database insertion can take about two days on a standard personal laptop. In an operational setting, it is more likely that we would not process a year's worth of tracks at once but rather analyze the tracks regularly as the information is gathered.

4.4 Magnets Grid

The inspiration for the Magnets Grid was the Dust&Magnets concept [24], which was designed to explore a multi-dimensional space of attributes. This VA tool favours the understanding a maritime situation beyond the exploration of traditional kinematic vessel properties. Interaction with the Magnets Grid can help identify trends and outliers in sets of hundreds of vessels according to multiple properties at once. In our demonstration scenario, vessels associated to a fictive suspicious country called "Jacardia" could be detected with the Magnets Grid using magnets that attracted vessels based on the number of references to Jacardian people and places contained in their profile.

The canvas space is filled with dots representing individual vessels, called the dust. Labelled magnets corresponding to vessel properties can be inserted into the canvas. Clicking the shake button will make the dust move according to the vessels' property values, as depicted in Figure 6. There is no limit to the number of magnets that can be used together, making this tool well fitted to explore multiple dimensions at once. New magnets can be created on the fly by selecting attributes in the vessel record.
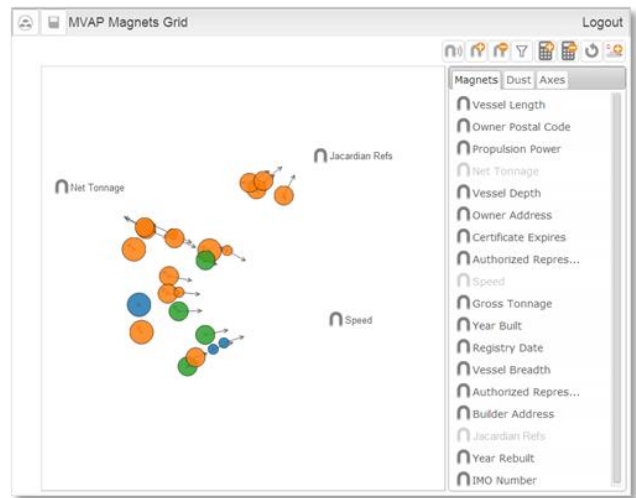

Figure 6. In Magnets Grid, the vessels are displayed as dots and magnets are dropped in the canvas to attract them based on vessel property values. The dots color and size can be associated to vessel properties. Here, the "Jacardian Refs" magnet reveals four outliers that are involved with this fictive suspicious country in our demonstration scenario.

We expanded the Dust&Magnets display with attraction arrows around dust elements to provide a visual cue indicating the attraction strength of the magnets. The arrows reduce the attraction ambiguity when a static snapshot of the Magnets Grid is captured.

We also augmented the tool with scatter plot capabilities and the possibility to constrain the dust movement to vertical or horizontal bands (or both). In Figure 7, associating the Vessel Type to the X-Axis will prevent the dots from leaving the bands to which they belong. This can enable insights about trends across the different categories represented by the bands. If no magnets are added to the canvas, associating the x-axis and y-axis to attributes will enable the use of Magnets Grid as a scatter plot tool (Figure 8).
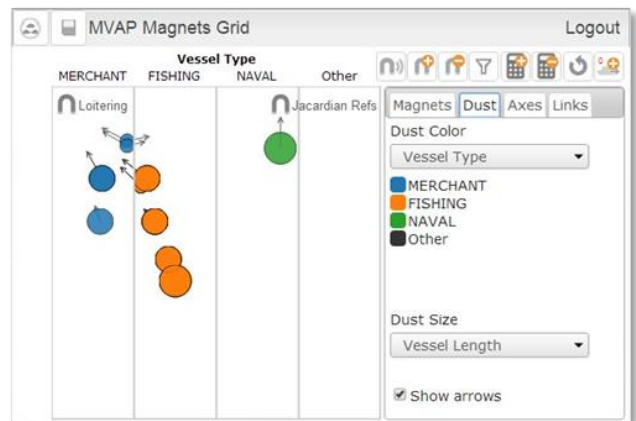

Figure 7. In Magnets Grid, the dots movement towards the magnets can be constrained by associating vessel properties to either the horizontal or vertical axis, or both. In this example, the vessel dots cannot leave the columns where they belong.
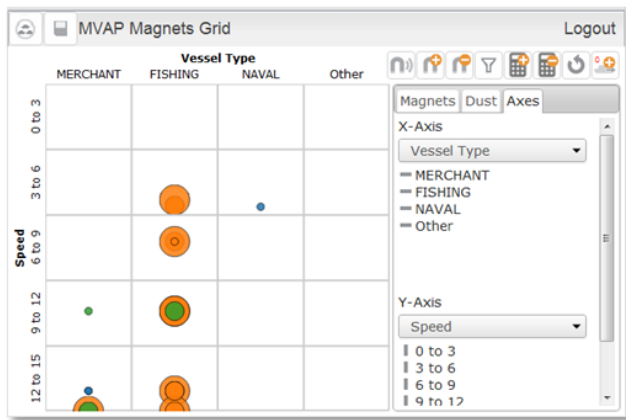
Figure 8. If we remove the magnets and select properties for both axes in Magnets Grid, we obtain a scatterplot display.

4.5 Visual Summary Cards and Record Browser

The intent of the Visual Summary Cards is to communicate the key characteristics of individual vessels in a concise visual format. The flip side of Visual Summary Cards also provides the factual textual information about the vessels. Information is formatted so that the analyst can look for normally present or absent elements rather than having to read each card. When available, a picture of the vessel is provided for visual identification. The top part of the cards contains icons for the vessel type, flag, as well as 24h and 96h call reports status. The word cloud contains the ports that were previously visited. The two icons at the bottom of the card are the Close Encounter Icon and a small snapshot of the vessel's track.

The cards can be displayed in the Record Browser, as shown in Figure 9. It allows an analyst to rapidly flip through a virtual deck of cards, enabling a visual scan for specific information. Dragging a particular card to the left part of the Record Browser facilitates visual comparison between vessels. Cards can be tagged as potential VOIs and a dot will appear on the bottom slider to identify those that were marked.
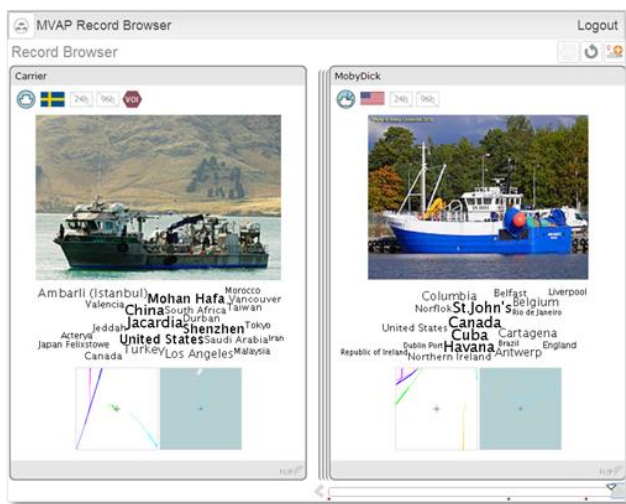

Figure 9. The Visual Summary Cards displayed in the Record Browser show the key vessel characteristics visually to allow for rapid scanning and visual comparison.

4.6 Multi-Timelines

The MVAP component for exploring temporal events is the Multi-Timelines tool (Figure 10). In this interactive visualization, each vessel has a horizontal timeline displaying its associated events. This tool is intended for closer analysis of a small number of vessels. The visual alignments of events along horizontal lines allow the visual comparison of these sequences for multiple vessels or even self-comparison when a vessel's line is duplicated. Unlocking the timelines enable comparison of sequences of events that happened at different time periods. This could lead to the identification of patterns or outliers.

In locked mode, dragging a timeline sideways will move all the other timelines synchronously. When the timelines are unlocked, we can drag them individually to align them on specific events that happened at different dates and visually compare how the situation evolved over time. The red line facilitates the manual alignment of individual timelines. Double-clicking on a specific event will also automatically align all the timelines to the nearest occurrence of this type of event in each timeline.
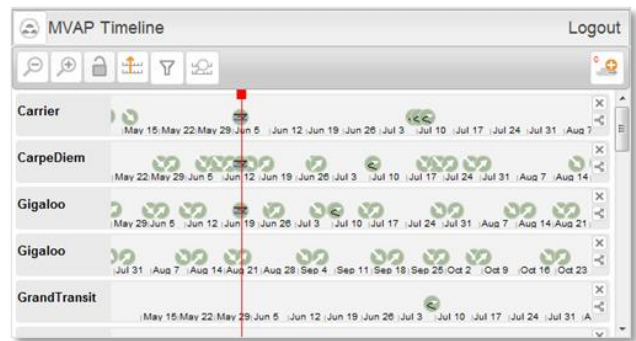

Figure 10. Multi-Timelines allow visual comparison of temporal events. A vessel's timeline can be duplicated to allow self-comparison and all the timelines can be unlocked to compare sequences of events happening at different time periods.

5. VALIDATION WITH TARGET USERS

The MVAP validation trials supported three objectives: evaluate the software usability, assess the potential operational value, and identify future improvements for the system.

Ten months before the validation trials, we held an early planning session onsite with nineteen maritime security analysts to guide the scenario and task development for the validation activity. They were briefed about the MVAP and their input influenced the tasks and datasets used in the validation trials.

5.1 Methodology

We employed a 'user jury' methodology to assess the MVAP, relying on the use of questionnaires and interviews with field experts [25]. We did not perform a direct comparison with operational tools because due to the lack of resources, many of the analyses that are offered by the MVAP are not currently being performed on a daily basis and there are no operational tools currently in use to support them.

Trials were conducted in groups of 3 to 5 participants in a single room. Each session lasted between sixty to ninety minutes and comprised three parts. It began with a hands-on training, followed by a set of tasks to be completed, and ended with participant

assessment acquisition through questionnaires and interviews. During the whole process, observers recorded relevant observations about the participants' actions, questions, comments, errors and unanticipated strategies.

The training and scenario tasks relied on a combination of real operational data that was ingested into the MVAP and fictive scenario data where the information was not available.

5.1.1 Hands-on Training
During the training part, a MVAP expert explained the purpose and concepts of the widgets, one at the time. The presenter performed relevant operations on a large display screen, while the participants followed along on their individual stations.

Participants were trained for as many operations as possible in a short time period of 30 minutes. Some widget operations were only performed by the presenter and not carried out by the participants due to limited training time. The widgets were presented in the following order: Analysis Set Manager, Map and Timeline, Record Browser, Magnets Grid, Multi-Timelines, and modified Map and Timeline using real operational data.

5.1.2 Scenario-Based Exercise
We gave participants a scenario worksheet that included a summary of the assigned exercise and a set of six questions to be answered using the skills that they had learned during the MVAP training. They had 15 minutes to complete the challenge tasks. Due to timing constraints, no tasks in the exercise involved the Multi-Timelines.

First, the users manipulated the specialized version of the Animated Map and Timeline to request all tracks on a certain date in a specified area. Then, they had to find and export all the vessels that contained specific keyword to an analysis set in the main MVAP application. They animated the tracks in the Map and Timeline to estimate the expected ports of arrival of these vessels on the map. After that, the Magnets Grid was used to characterize the ships using a combination of construction properties such as build year and tonnage. Finally, the analysis concluded with a scan of the Visual Summary Cards to identify vessels with particular characteristics such as a specific flag.

5.1.3 Questionnaires and Interviews
After the tasks were completed, we handed participants the usability survey and a ranking sheet asking them to rank the usefulness of individual widgets and to write any comments they may have about them.

The sessions concluded with a hot wash group discussion where all participants were invited to share their thoughts and voice any questions they had about the MVAP.

5.2 Assessment Metrics
Three types of metrics were collected to assess the MVAP prototype. First, trial participants made an overall subjective assessment of the perceived effectiveness, efficiency, correctness, satisfaction, and trust of the MVAP features using the internationally recognized System Usability Scale (SUS) questionnaire [26, 27].

Then, they gave an individual rating to each widget according to their perception of the potential usefulness of each tool. The proposed scale included 3 values: "Not Useful (0)", "Possibly Useful (1)" and "Very Useful (2)". They were also invited to add comments about each widget.

Observers took notes to document all the observations, comments and questions that were expressed by participants at any time during the whole process. They also recorded the errors the participants made as well as the unanticipated strategies that they exhibited while working with the MVAP. These comments and observations provided the basis for an informal but insightful assessment.

5.3 Participants Selection
Sixteen maritime security specialists and analysts participated in the trials held on-site at the Halifax MSOC facility on November 13th and 14th, 2013. The positions of the participants included analysts, intelligence officers, Navy lieutenants, a watch officer, a coordinator, a maritime picture manager and maritime information management systems developers. The participants were very knowledgeable about the maritime domain, but were not familiar with advanced interactive visualizations. There was at least one representative from each of the five federal partners involved in the Canadian MSOCs [2]:

• Canada Border Services Agency;

• Canadian Coast Guard;

• Department of National Defence;

• Royal Canadian Mounted Police; and

• Transport Canada

6. TRIAL RESULTS
6.1 Overall MVAP Evaluation
Fourteen of the sixteen participants filled the System Usability Scale (SUS) questionnaire. Globally, the MVAP review was very positive (Figure 11). It obtained an average SUS score of 76, which means that the MVAP scored better than 75% of new software releases (using statistics from [26]). This is considered "Excellent" according to [28]. Observers noted that some participants were even trying features without waiting for the training, hinting that the user interface was intuitive and easy to understand.
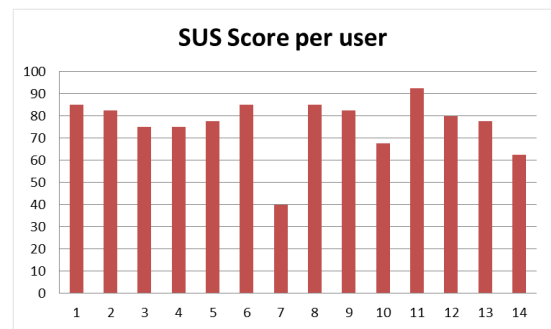
Figure 11. System Usability Score obtained from 14 participants for the overall MVAP evaluation.

Participants were very enthusiastic about the MVAP and indicated that they would definitely use it if it was made available to them. Their verbal and written comments suggested that it offered significant improvements over the current MSOC tools. Many participants were already thinking ahead about how the new features offered by MVAP could be integrated into the

MSOC. They provided insightful suggestions for extending the prototype's capabilities and adapting it to their specific operational context requirements.

6.2 Individual MVAP Widget Assessments

The five MVAP widgets have a high expected operational usefulness as a majority of participants ranking them as "Very useful" (Figure 12). The average rankings ranged between 1.5 and 1.9. One participant had to leave and did not fill this form.
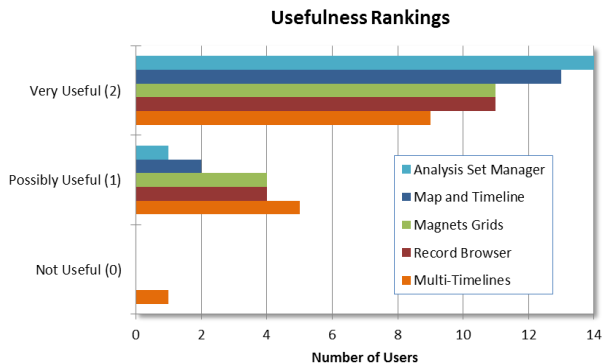

Figure 12. Usefulness rankings for individual widgets: 15 participants assessed each widget individually according to the expected usefulness that they perceived for their own operational work.

6.2.1 Analysis Set Manager

The Analysis Set Manager was among the top ranked widgets with an average of 1.9. Participants understood its role in structuring the analysis data and were quickly able to create analysis sets with the widget. They commented that the widget was clear and easy to understand, and would be great for grouping certain datasets. They recommended adding a number of import and export data formats to increase the analysis sets sharing capability between analysts from different departments or with other systems.

6.2.2 Animated Map and Timeline

The Animated Map and Timeline was also top ranked with a 1.9 average score. It was the widget that generated the most comments and some participants called it "the best app of all". Being able to visualize the time evolution of vessel tracks was one of the most esteemed capabilities. The search feature for close encounters was greatly valued and they stated that it was not possible to do this with their current tools. Participants were especially interested in the modified widget version that used their operational data.

Although moving time back and forth was very popular, the time slider interaction was difficult to master rapidly and led to many manipulation errors. To improve it, they suggested adding a time interval selection field to enter the initial settings.

Not much time was spent on Close Encounter Icons and the patterns created by real vessel tracks were much harder to interpret than Figure 5 would suggest. It is possible that after a longer exposure the patterns in the icons may become familiar. However, the MSOC environment where the turn-over in manpower is high makes this visual representation less desirable. Regarding the Route Ribbons, a similar visual representation is now part of their recognized maritime picture and it appears to be effective.

The comments highlighted how the interactive geo-temporal visualization could help making sense of a developing situation over time. Potential uses were suggested for marine security and regulation operations such as detecting polluters, determining baseline activities through pattern of life analysis, and helping communicating analysis results more clearly in briefings.

6.2.3 Magnets Grid

Although, it scored an average ranking of 1.7, Magnets Grid was very popular among participants, many of them calling it "awesome". This was partly due to its high novelty: there is no comparable visualization tool at the MSOC that enables exploration of these types of vessel characteristics visually.

The visualization looked complex at first but observations of self-learning from participants indicated that it was surprisingly easy to understand. In a very short time, the participants were very proficient with the Magnets Grid and had no major difficulties in completing the related tasks. The attraction arrows concept was not clear to at least one user. Another participant pointed out a weakness that appears in the presence of a very strong outlier, allowing it to dominate the canvas and force the others dots into a tight cluster.

Overall, participants thought the concept was very interesting, but some did not see how it would be useful to them because they did not expect to have access to a rich enough array of operationally relevant data to make the Magnet Grid effective.

Other participants suggested several ways to use the Magnets Grid for maritime security operations, such as comparing vessels, multi-parameter searching and fuzzy analysis. They even proposed new types of calculated attributes for magnets that would turn some geographic properties of vessel tracks into data usable with Magnets Grid, such as boundary crossing detections.

6.2.4 Visual Summary Cards and Record Browser

The Visual Summary Cards got an average ranking of 1.7. Participants thought it was useful and easy to understand but expressed concerns about the availability of the data used in the cards display. This is very important because the usefulness of this visualization is highly dependent on having detailed dynamic information about vessels. Sharing watch lists was proposed as an example of potential operational application.

Some participants wished the card's layout was user configurable so they could tailor it to their analysis needs. A comment was made about a similar tool being used already, although no details were provided regarding its usefulness or adoption rate among target users. A participant wanted to be able to look at both sides of the cards simultaneously.

6.2.5 Multi-Timelines

The Multi-Timeline scored lower than all the other widgets, with an average of 1.5. It is also the only tool that received a "Not Useful" rating. Participants understood that the widget's purpose was to analyse temporal patterns, but they explained that this kind of analysis is not frequent in their work. They still proposed potential ways to use it by adding geographically triggered events such as boundary crossings or close encounters detection. They valued the ability to unlock and shift temporal lines independently.

The Multi-Timelines widget was taught at the end of the training session, very often with little or no time for the user to really try it

and was not covered in the challenge tasks. This could partially explain the low ratings from the users.

7. LESSONS LEARNED AND DISCUSSION

7.1 Modular Prototype
Separating the visualization requirements identified into a suite of smaller widgets resulted in a modular prototype. This modular approach gives us the flexibility to provide interested users with only the features that they want without requiring them to adopt a complex application framework.

Focussing on individual widgets allowed us to concentrate on the different aspects of the visual analysis requirements and to assess the effectiveness of the visual representations and interactions independently for each widget. An added benefit is to facilitate widgets reuse for other application domains (see section 8.4).

7.2 Importance of a Working Prototype in Visual Analytics
The ease with which trial participants understood the Magnets Grid widget was very surprising to us. Much earlier in this project, when we first explained the Magnets Grid concept to other maritime specialists in a presentation, they did not grasp its purpose and had difficulty envisioning its use. We thought this tool would require very detailed training and expected many participants to fail the related tasks.

This experience highlights the importance of showing a working prototype using realistic data to target users and not relying solely on their perception of a paper design.

7.3 Real Data Matters for Credibility
Using fake but realistic data helped users understand the purpose of the MVAP when they followed the training. However, we noticed a significant increase in the participants' attention when we moved to the modified Map and Timeline widget that uses their data.

Although real data was not available for all the features that we wanted to demonstrate, showing at least a part of the MVAP capabilities using real operational data was sufficient to prove that the prototype was not only nice research software, but had the potential to become an operational tool. Because we went through the development required to adapt our prototype, we were prepared to address their concerns about the MVAP being able to handle their large datasets.

At the other end of the spectrum, the Multi-Timelines was not showcased in the challenged tasks and users did not really get a chance to experience it with meaningful data. We think this is partly why it got a lower rating than all the other widgets.

7.4 Other Application Domains
A few participants' comments suggested that the MVAP could be useful beyond the MSOC context. By focusing on the analytic tasks to perform rather than the specifics of vessels information, we designed the widgets in a very generic fashion, expecting some to be used in a non-maritime context.

The adaptation of the MVAP widget to the social network analysis in a counter-insurgency context demonstrated the generic property of the visual analysis concepts proposed [29]. It should be noted that moving to a new application domain still requires development work to ingest the different data format and modifications to the visual interface, even though the basic concepts are the same. Notably, the Visual Summary Cards layouts need to be tailored for each type of analysis entity.

8. CONCLUSION
A study of maritime domain analysis performed at the MSOCs revealed that VA has the potential to enable better detection and analysis of marine threats. After identifying requirements related to visual detection of anomalous vessel behaviour and vessel of interest analysis, we designed the Maritime Visual Analytics Prototype using a modular approach. The capabilities of the MVAP are provided by a series of individual specialized visual analysis tools, leveraging both kinetic vessel track data and non-kinetic vessel information.

The Analysis Set Manager is the launching point for the other widgets and offers a hierarchical presentation of the vessel sets to analyse. The Animated Map and Timeline widget contains the geographical display that is central to the analysis and allows users to animate vessel tracks interactively while providing the Close Encounter Icons and Route Ribbons visual representation to highlight potential anomalous vessel activities. Using the Magnets Grid, factual information about vessels can be explored to detect trends and outliers across multiple dimensions simultaneously. The key characteristics of individual vessels appear in Visual Summary Cards. The Record Browser enables a quick scan of a vessel cards deck, as well as the visual comparison between cards for specific visual cues. Finally the Multi-Timelines widget provides an interactive interface to analyse and compare sequences of temporal events related to vessels.

Sixteen maritime security analysts and specialists assessed the potential for operational deployment of the MVAP employing a user jury methodology. They went through a hands-on training, a set of tasks to perform individually and filled out surveys about the tools.

Based on the positive validation trials results, we recommend that the MVAP be made available to MSOC developers so they can turn it into an operational tool.

9. ACKNOWLEDGMENTS

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