Optimization of surveillance vessel network planning in maritime command and control systems by fusing METOC & AIS vessel traffic information

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***Abstract*—This paper presents the recent developments of an Optimal Path Planning - Decision Support System (OPP-DSS). The designed framework is based on multi-objective optimization algorithms providing a set of Pareto efficient solutions representing a trade-off among mission objectives. Meteorological and Oceanographic (METOC) and Automatic Identification System (AIS) vessel traffic data are integrated and exploited inside the planning process to improve surveillance in piracy risk areas. Tests in an operational scenario with real-world data provide indication of the effectiveness of the approach.**

Keywords*—*environmental forecasts, risk surfaces, multi-objective optimization, sensor networks, path planning, counter piracy.

I. Introduction

Piracy in the maritime domain continues being a problem of worldwide concern. Daily piracy activities are recorded in the areas covered by the principal commercial routes along the earth, even when counter piracy operations are being performed. The Arabian Sea and the Gulf of Aden have been defined as high risk areas in the Best Management Practices (BMPs) by the Maritime Security Centre Horn of Africa (MSCHOA) [1]. Nowadays these areas are secured by several international forces: the European Union Naval Forces (EUNAVFOR) of Operation Atlanta [2], the Combined Task Force - 151 (CTF-151) [3] and the NATO - Operation Ocean Shield (NATO-OSS) [4].

To provide support to maritime command and control systems during counter-piracy operations, different tools have been described in the open literature. In 2009, The U.S. Naval Oceanographic Office (NAVOCEANO) developed a forecasting product named Piracy Performance Surface (PPS) [5]. The PPS uses forecasts of winds and seas to map the locations more suitable to piracy activity, and incorporates information of confirmed pirate activity in the form of attack, attempted attack, and suspicious activity. In 2011, NAVOCEANO developed the Next-generation PPS (PPSN), then renamed Pirate Attack Risk Surface (PARS) [6]. In [7] the authors proposed an algorithm/procedure to allocate interdiction and surveillance assets to minimize the likelihood of a successful pirate attack over a fixed planning horizon. In 2012, the NATO Science and Technology Organization (STO) Centre for Maritime Research & Experimentation (CMRE) developed an Optimal Path Planning - Decision Support System (OPP-DSS) to support maritime command and control operations. The OPP-DSS is an information system that supports organizational decision-making activities. It acts as a planning system for Surveillance Network of Assets (SNA) to optimize the coverage of high risk areas.

This work presents the new developments in the OPP-DSS. Specifically, this article illustrates how heterogeneous sources of information are integrated inside the planning process to improve surveillance in piracy risk areas. Furthermore, it proposes a methodology of integration of Meteorological and Oceanographic (METOC) and vessel traffic density data to predict regions where pirates may be present or may strike next.

The paper is organized as follows. Section II describes the proposed framework, its structure and presents the optimization method involved. Section III illustrates how heterogeneous information sources are processed and it proposes a test case based on real data to verify the effectiveness of the tool. Section III summarizes the work and draws the main conclusions.

II. System description

The OPP-DSS is a planning system for controllable moving assets designed to help decision-makers in different operations performed in command and control systems. Fig. 1 shows the main components of the proposed framework. It is composed of three main interconnected components. Starting from the top, the *Information Space (IS)* provides all the available information data about the Area Of Interest (AOI). This component is structured in different heterogeneous information layers. Each layer describes a particular characteristic/parameter and how it changes in space and time over the AOI. The OPP-DSS uses in this case as information layers:

- *METOC forecasts* proving the environmental conditions over the AOI for a finite temporal window.

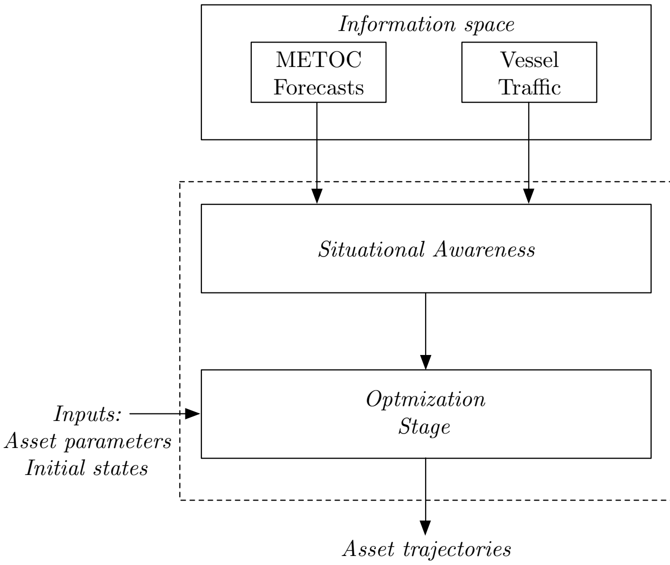


Fig. 1: Optimal Path Planning - Decision Support System (OPP-DSS) framework.

- *Traffic layer* describing the estimated traffic density over the AOI.

Previous works at CMRE [8], [9] describe prior developments on the OPP-DSS, where the asset planning is based on risk surfaces, such as Pirate Activity Group (PAG) maps or Satellite Automatic Identification System (AIS) performance surfaces. The *Situational Awareness (SA)* component fuses different information layers and generates enriched risk surfaces. These data are exploited in the *Optimization Stage (OS)*. This stage implements a multi-objective evolutionary optimization algorithm able to minimize/maximize a set of conflicting metrics (e.g. total mission cost and network spatial coverage) and work with a population of solutions instead of a single solution. The selected algorithm is the Improved Archive-based Multi-objective Genetic Optimizer (AMGA2) [10]. AMGA2 has the advantage of not requiring a fine-tune of the algorithm parameters. Indeed, the only parameters exposed to the user are the maximum number of function evaluations and the number of desired solutions. The AMGA2 is integrated into the OPP-DSS and it produces a set of waypoints forming the asset path. As final step, the OS is completed by an asset trajectory simulator which produces the full trajectories starting from the provided waypoints.

The formulation is as follows: consider a SNA composed of N assets where $\mathbb{Z} \subseteq \mathbb{R}^{M\times N}$ ($M = 2\times Q$) represents the set of all possible trajectories within the temporal window of Q steps; a solution matrix $\mathbf{Z} \in \mathbb{Z}$ is of the form $\mathbf{Z} = [\mathbf{z}_1, \mathbf{z}_2, \dots \mathbf{z}_N]$ where $\mathbf{z}_i = [x_1, y_1, x_2, y_2, \dots, x_Q, y_Q]_i^T$ represents the set of waypoints (x, y) forming the trajectory for the asset i. The vector of objective and constraint functions are defined by $\mathbf{f}(\mathbf{Z})$ and by $\mathbf{g}(\mathbf{Z})$, respectively. Then, the multi-objective optimization problem is written as follows:

$$\begin{aligned} \min_{\mathbf{Z}\in\mathbb{Z}} \quad & \mathbf{f}(\mathbf{Z}) \\ \text{subject to} \quad & \mathbf{g}(\mathbf{Z}) \leq 0 \\ & \mathbf{z}_i^L \leq \mathbf{z}_i \leq \mathbf{z}_i^U \qquad i = 1, \dots, N \end{aligned} \tag{1}$$

where $\mathbf{z}_i^L$ and $\mathbf{z}_i^U$ are the vectors of the lower and upper bound limits of the components of $\mathbf{z}_i$. In this application, the goal of the OPP-DSS is to maximize the amount of surveyed traffic and total area coverage, while minimizing the total mission cost and placing the assets in the safest areas from a navigation point of view (e.g. low significant wave height). Eq. (2) shows the four metrics involved in the process. The total mission cost, $C(\mathbf{Z})$, evaluates the costs involved in the asset deployment considering the fuel consumption. In this implementation, the cost of the asset i is equal to the path length $L(\mathbf{z}_i)$ weighted by the asset linear cost C_i. The environmental risk $R(\mathbf{Z})$ asses the risk of the SNA on the METOC surface ($M(t)$). The total area coverage, $A(\mathbf{Z})$, evaluates the covered area by all the assets along the selected temporal window . The simulated assets are equipped with sensing capabilities with maximum range of 100 km. The surveyed traffic, $T(\mathbf{Z})$, estimates the maritime traffic load in the covered areas by the SNA along the temporal window.

$$\begin{aligned} \min_{\mathbf{Z}\in\mathbb{Z}} \quad & C(\mathbf{Z}) = \sum_{i=1}^{N} L(\mathbf{z}_i) C_i \\ \min_{\mathbf{Z}\in\mathbb{Z}} \quad & R(\mathbf{Z}) = \sum_{i=1}^{N} \int_{t_s}^{t_e} R(\mathbf{z}_i(t)) \mathrm{d}t \\ \max_{\mathbf{Z}\in\mathbb{Z}} \quad & A(\mathbf{Z}) = \sum_{i=1}^{N} \int_{t_s}^{t_e} A(\mathbf{z}_i) \mathrm{d}t \\ \max_{\mathbf{Z}\in\mathbb{Z}} \quad & T(\mathbf{Z}) = \sum_{i=1}^{N} \int_{t_s}^{t_e} T(\mathbf{z}_i(t)) \mathrm{d}t \end{aligned} \tag{2}$$

For the sake of completeness, Eq. (3) reports the definition of $\mathbf{f}(\mathbf{Z})$ according to the objectives defined above:

$$\mathbf{f}(\mathbf{Z}) = [C(\mathbf{Z}), R(\mathbf{Z}), -A(\mathbf{Z}), -T(\mathbf{Z})] \tag{3}$$

The OPP-DSS produces a set of Pareto efficient solutions. Each solution represents a trade-off among the different mission objectives. Fig. 2 shows an example of the Pareto front illustrated through a Hyper-Radial Visualization (HRV) approach [11], which maps multi-dimensional data into a two-dimensional space. *HRC_1* groups into one set the METOC and Traffic risks. *HRC_2* groups into one set the total area coverage and the total mission cost. The highlighted areas point out the solutions characterized by low cost and area coverage but with high risks (red ellipse), and the ones characterized by low risks but with high coverage and costs (yellow circle). An important task is the selection of the best trade-off among the possible solutions.

III. RESULTS

This section presents a scenario wherein the OPP-DSS can be used. The tool is designed to plan the trajectories of SNA based on METOC forecasts and AIS traffic data over the selected AOI. The following subsections detail the principal aspects of the scenario, the sources of information used and the results obtained.

A. Description of the scenario

A scenario is set up to test the capabilities of the OPP-DSS. A good candidate as AOI is the Arabian Sea and

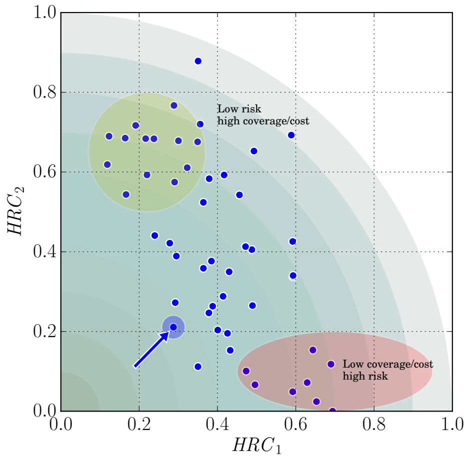


Fig. 2: Example of the estimated Pareto front after 30,000 evaluations. The axes indicate the competing objectives. The total number of solutions is 50.

Gulf of Aden areas. As a matter of fact, along these areas a considerable number of piracy activity reports have been recorded. Furthermore, these areas are crossed by the main trade routes connecting West and East through the Suez Canal and the Red Sea. The limits of the AOI are:

- Latitude range: from 0° to +20°N.
- Longitude range: from +50°E to +70°E.

The SNA is composed of six assets. Simulated assets include frigate class ships equipped with sensing capabilities, having a maximum range of 100 km, constant detection probability $P_D = 0.8$. The feasible regions for control actions are $\Omega_s = [5, 10]$knots and $\Omega_\theta = [\bar{\theta} - 70°, \bar{\theta} + 70°]$deg, where $\bar{\theta}$ is the ship current heading angle of arrival to the last reached waypoint. The scenario starts the 22 March 2012 at base time 00:00:00Z and ends the 24 March 2012 at base time 00:00:00Z. Fig. 3 shows the initial configuration of the SNA randomly generated. Along the selected temporal window, a pirate attack was recorded by the NATO Shipping Center (NSC)[12], on 23 March 2012 at base time 04:00:00Z (Alert code 024/12). Figure 4 shows the attack position over the AOI.

Each day a new METOC forecast is provided by National Oceanic and Atmospheric Administration (NOAA) covering a temporal window of three days. The latest downloaded METOC forecasts are used by the SA to update the risk surface. The selected scenario covers three days. To obtain the best results each day a new simulation is run considering as vessel start locations the ones reached by the assets at the end of the previous day. Fig. 5 illustrates schematically the execution flow: the blue arrows point out when new METOC forecasts are available and downloaded, whereas the red arrow refers to the attack 024/12. The white rectangles point out the OPP-DSS executions and the days covered by each one. The gray rectangles point out the parts extracted as a result from each OPP-DSS execution.

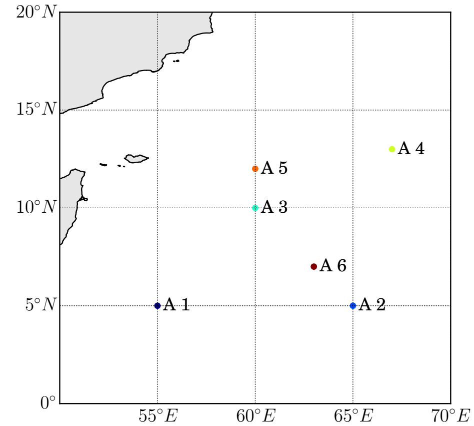


Fig. 3: Initial configuration of the Surveillance Network of Assets.

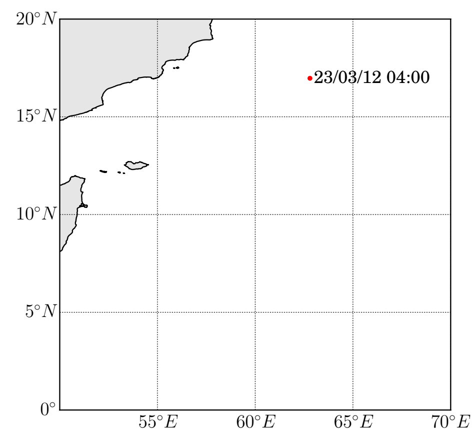


Fig. 4: Pirate attack recorded between March 22, 2012 and March 24, 2012.

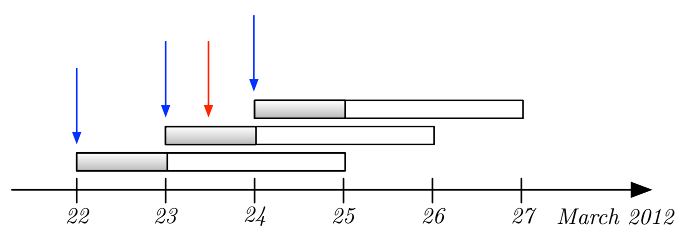
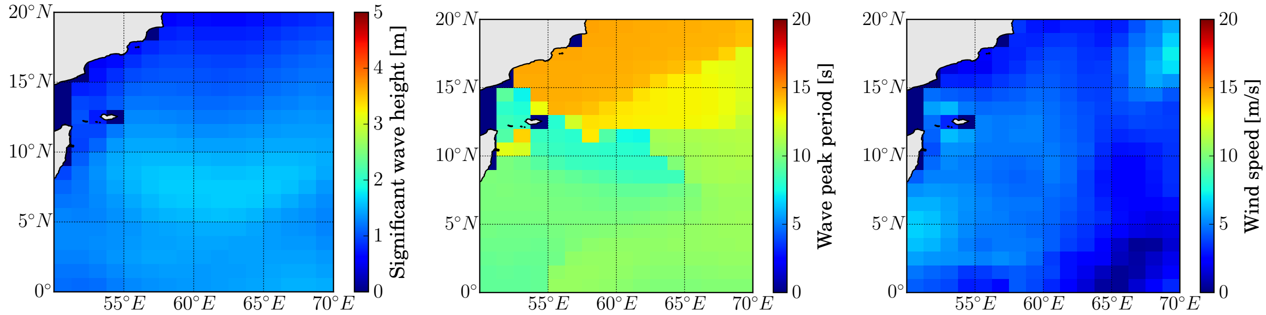


Fig. 5: Execution steps of the OPP-DSS for the selected scenario.

B. Sources of information

1) METOC: The Meteorological and Oceanographic information layers provides the environmental conditions over the AOI for a finite temporal window. This information is publicly provided by NOAA. The data set consists of worldwide grid of METOC hindcasts generated using the WAVEWATCH III model [13]. This information layer is composed of different sub-layers. In [14] is demonstrated that the piracy activities are mostly affected by the following METOC variables: the wind speed (absolute value) [ms^{-1}], the significant wave height [m]



(a) Significant wave height.

(b) Wave peak period.

(c) Wind speed.

Fig. 6: Snapshot of the METOC variables.

and the wave peak period [s]. For the purpose of this work the same METOC variables are considered. The OPP-DSS is able to download from the NOAA public archive the last available forecast and provide to the user an updated output. The forecasts are characterized by a temporal resolution of three hours for a period of 3 days (72 hours). Fig. 6 provides a snapshot of the three features used in process.

2) Vessel traffic layers: Automatic Identification System (AIS) is a self-reporting messaging system originally conceived for vessel collision avoidance. Vessels transmit static (name, class, flag state, dimensions, etc.) and dynamic (location, speed, course) information at intervals dictated by the AIS protocol.

The NATO STO CMRE collects historical AIS data from multiple networks, including the Maritime Safety and Security Information System[1] sensor network, external providers and single ground stations. These, together with other experimental data, are used for scientific purposes and the development of algorithms. AIS technology provides a vast amount of near-real time information, having the potential to transforming data into meaningful information to support operational decision makers. For reference we report in Fig. 7 the density of traffic in the area of interest collected during six months at the NATO STO CMRE. Recently, the vast amounts of AIS data have been exploited to study the patterns of vessel traffic and automatically detect anomalous vessel movements [15], [16], [17]. In this study, we combined together terrestrial and satellite AIS data to derive vessel density maps of the historical traffic in the area distinguished by the main ship-types. For the most common types of vessels (i.e., cargo, tanker, tug, passenger, fishing category), maritime traffic density maps in the Indian Ocean were derived, on a monthly basis from the data collected during 2012, and on a 8-hours basis from the data recorded between March, 20^{th} and 30^{th} 2012, with a resolution of 15 nmi (one-fourth-degree per pixel). Fig. 7 shows an example of such traffic layer for a longer time frame and in a much higher resolution: each pixel in the image covers a 4 nmi (one-fifteenth-degree) square on the ground, with a color that is logarithmically proportional to the number of ships whose reported position fall within the footprint; the figure has been generated using AIS data collected during six months in 2012. A planned extension of the analysis will include the directionality of vessel routes into the traffic layer by using, as an example, a vessel pattern of life extracted via the CMRE tool Traffic Route Extraction and Anomaly Detection (TREAD) [15]. Additional relevant features (e.g., average speed of the vessels along the route and/or cargo of the vessels) can be taken into account in order to study the correlation of these features with the piracy risk in the area.

[1]Maritime Safety and Security Information System (MSSIS) is an unclassified government-to-government near real-time data collection and distribution network for AIS data, based on the contributions of a global network of member nations. MSSIS is mainly a shared network of coastal AIS receivers.

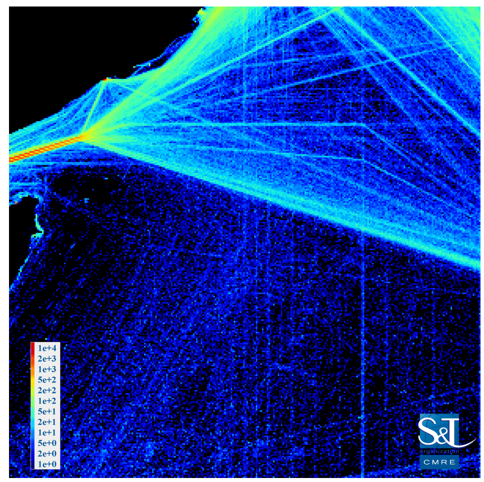


Fig. 7: Density of AIS messages collected from multiple AIS networks from April to September 2012 in the area under analysis. Each pixel covers a 4 nmi (one-fifteenth-degree) square on the ground and its color is (logarithmically) proportional to the number of ships whose reported position fall within its footprint.

C. Risk surfaces at the Situational Awareness stage

The Situational Awareness (SA) is the system component responsible to fuse the information from the IS and generate risk surfaces. The METOC layer is composed of three information sub-layers describing the environmental conditions for a finite temporal window. The available features are: the wind speed ($u_{10}(t)$), the significant wave height ($H_S(t)$) and the wave peak period ($T_m(t)$). The aim of the SA is to compute an unique risk surface, named *METOC Surface*. The new surface has the main purpose of describing which areas of the AOI are subjected by high risk for navigation and which ones are safe. The areas characterized by high risk are delineated by high wind speed and significant wave height values and low wave peak period values. A fast computing method of the METOC surface $M(t)$ is shown in Eq. (4).

$$M(t) = k_{u_{10}} \frac{u_{10}(t)}{N_{u_{10}}} + k_{T_m} \left(\mathbf{1} - \frac{T_m(t)}{N_{T_m}} \right) + k_{H_S} \frac{H_S(t)}{N_{H_S}} \quad (4)$$

The METOC surface defined in Eq. (4) is the weighted sum of the normalized METOC sub-layers. The normalization factors $N_{u_{10}}$, N_{T_m} and N_{H_S} are defined during the OPP-DSS initialization stage. The values $k_{u_{10}}$, k_{T_m} and k_{H_S} are set by the decision-maker to choose which are the parameters more important during the surface computation. Generally, considering a safety point of view, the most important parameters is the significant wave height. The other features affect in a lower magnitude the safety but have considerable influence in the fuel consumption. The user has the responsibility of selecting the best trade-off between cost and safety. The resulting surface is used as parameter in the evaluation of the environmental risk ($\min_{\mathbf{Z} \in \mathbb{Z}} R(\mathbf{Z})$) in the OS. Fig. 8 shows an example of a computed METOC surface with $k_{u_{10}} = 3$, $k_{T_m} = 1$ and $k_{H_S} = 5$ on 23 March 2012 03:00:00Z. In this case the significant wave height is the parameter with higher impact on the METOC surface. The light blue area is extended due to the minor contribution of the wind speed and the wave peak period. The Traffic Layer describes the number of recorded

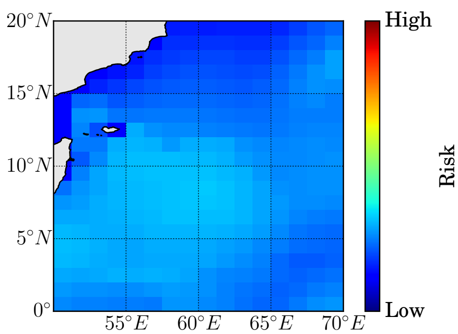


Fig. 8: METOC surface on 23 March 2012 03:00:00Z.

vessels crossing the AOI in a finite temporal window. The *Vessel traffic surface* is equal to the vessel traffic layer scaled by a normalization factor N_T (e.g. maximum number of crossing vessels in a temporal window of specified duration). This surface is used as parameters in the evaluation of the amount of surveyed traffic ($\max_{\mathbf{Z} \in \mathbb{Z}} T(\mathbf{Z})$). Fig. 9 shows an example of the traffic surface. The METOC surface defines the areas of the AOI which are suitable for piracy activities. These areas could be located far from the principal trade routes and/or may be characterized by the absence of any vessels. The introduction of Vessel Traffic surface overcomes the identified weakness moving the focus in the areas characterized by environmental conditions favorable for piracy activities and by the presence of vessels.

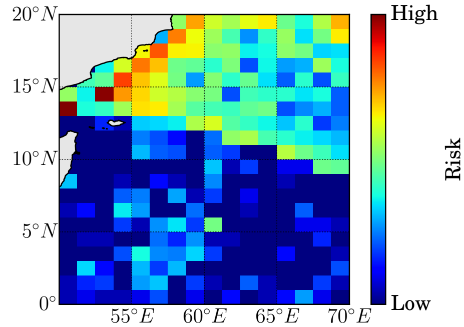
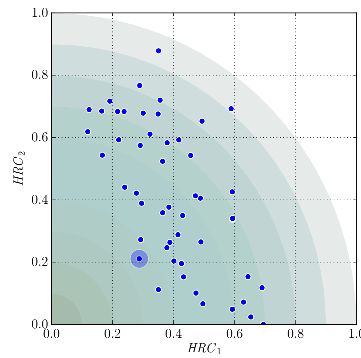
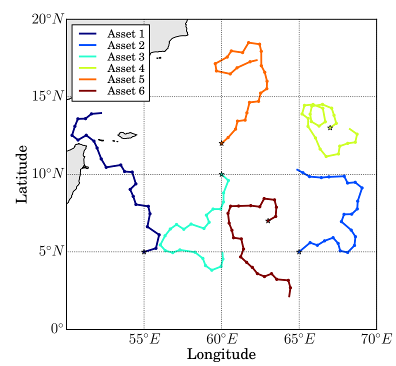


Fig. 9: Traffic risk surface.



(a) Hyper-Radial Visualization of the Pareto front.

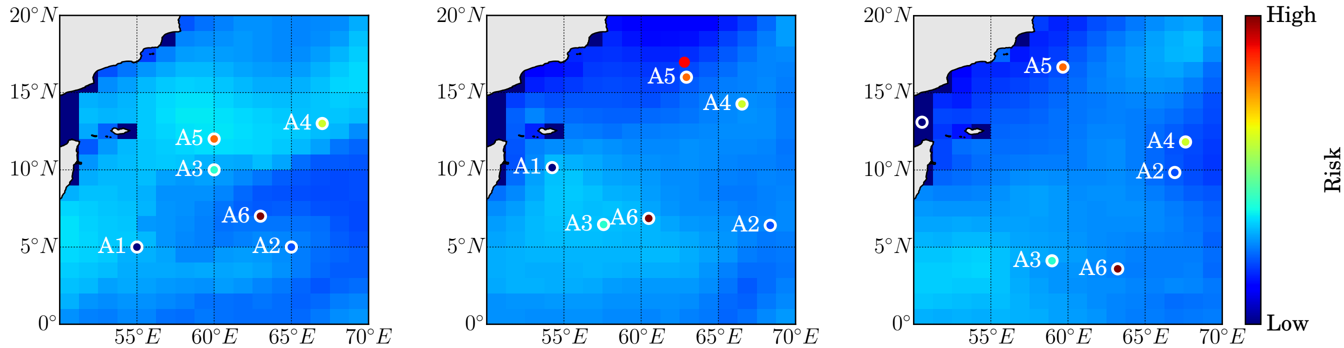


(b) Planned trajectories from one selected solution of the Pareto front.

Fig. 10: Results of the multi-objective optimization problem using METOC and Vessel traffic layers. Fig. 10a shows the Pareto front through HRV. Fig. 10b shows the trajectories of the selected solution, highlighted in Fig. 10a by a circle.

D. *Results for the scenario*

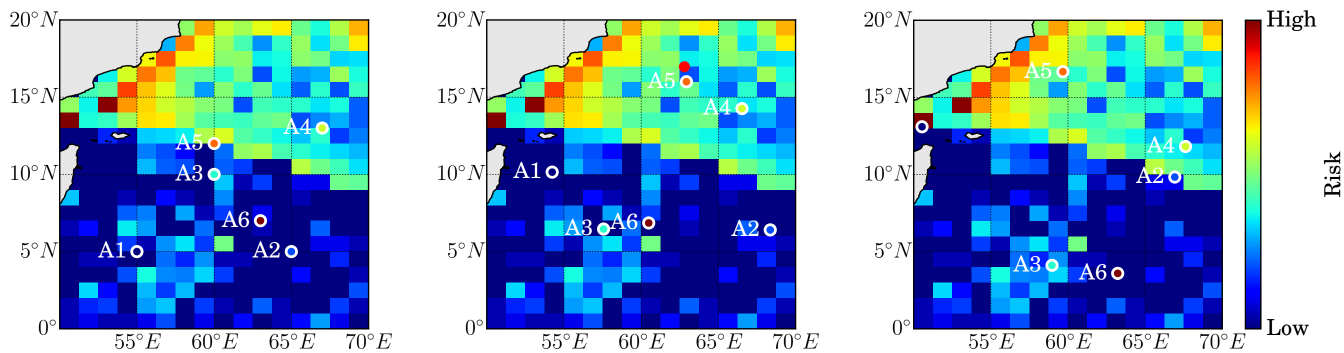
The goal of the OPP-DSS is to maximize the amount of surveyed traffic and total area coverage, while minimizing the total mission cost and placing the assets in the safest areas from a navigation point of view. A multi-objective optimization problem is set-up. Fig. 10 illustrates the process results. Fig. 10a shows the approximated Pareto front through the HRV approach after 50,000 evaluations. The OPP-DSS was set to provide 50 solutions along the Pareto frontier.



(a) 22 March 2012, 00:00:00Z - METOC overlay.

(b) 23 March 2012, 00:03:00Z - METOC overlay.

(c) 24 March 2012, 00:09:00Z - METOC overlay.



(d) 22 March 2012, 00:00:00Z - Traffic overlay.

(e) 23 March 2012, 00:03:00Z - Traffic overlay.

(f) 24 March 2012, 00:09:00Z - Traffic overlay.

Fig. 11: Snapshots of the assets locations and the pirate attack NSC024/12 (red placemark) at different time steps plotted over the associated METOC risk surface (Figs. 11a - 11c) and over the vessel traffic surface (Figs. 11d - 11f).

The selected solution is highlighted in blue background. It represents the best trade-off among the objectives involved the problem. Fig. 10b depicts the trajectories associated to the selected solution. A first qualitative overview of the solutions shows the ability of the planning system to distribute the assets to cover different sectors of the AOI and maximize the area coverage.

Fig. 11 illustrates the position of the SNA using as overlay the METOC (Figs. 11a - 11c) and the traffic surfaces (Figs. 11d - 11f) at three time-steps of the temporal window [22 March 2012 00:00:00Z, 24 March 2012 00:00:00Z]. In particular, Figs. 11b and 11e show the spatial configuration of the SNA at the time-step of the attack 024/12 (plotted as a red point). The attack is located in the north of the AOI. This area is characterized by low environmental risk (METOC surface) and medium traffic density. The OPP-DSS is able to plan the trajectories in order to satisfy the objectives defined. In fact, the assets are positioned in the areas delineated by low risk from a navigation point of view and high traffic density which area suitable for having piracy activity, as observed in this example. Furthermore, the system is able to position an asset (Asset 5) near the attack location. The distance between the nearest asset and the pirate attack 024/12 is below the detection range (107 km), therefore the presence of piracy activity can be detected.

IV. Conclusions and Future Work

This study presents the new developments and progresses of the OPP-DSS at NATO STO CMRE. The framework is able to successfully manage heterogeneous data and provide useful information to decision-makers when planning maritime operations in command and control systems. The results show that the system is able to plan SNA trajectories in order to survey areas characterized by high piracy risk. The results provide a preliminary indication how useful can be the proposed approach. Future work will be focused on the use of a statistically significant dataset in order to characterize the performance of the proposed system.

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