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METOC-driven Vessel Interdiction System (MVIS): Supporting decision making in Command and Control (C2) systems

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Abstract—**This paper presents a decision support system (DSS) to help Command and Control (C2) operators. Hereby, the METOC-driven vessel interdiction system (MVIS) is presented. It is aimed to help the decision-making process in case of interdiction operations so that the success rate increases. In particular, MVIS yields the best location along a predicted path to interdict a vessel in the best meteorological and oceanographic (METOC) conditions and/or taking the fastest track. The system scheme includes two main processing stages: the routing algorithm and the decision-making stage. The routing algorithm finds out the minimum cost -optimal- routes through an optimization algorithm to the predicted interdiction locations. The algorithm is guided by means of a navigation model that employs METOC variables, such as the significant wave height or the wind. A numerical ocean model (NOM) provides the METOC forecasts. The decision-making stage arranges the proposed solutions according to a risk metric, which is computed by an objective function. The best solution corresponds to the lowest metric. As a final step, the ranking of solutions is visually presented to the operator. To illustrate the MVIS performance, a case study within the Mediterranean Sea is developed that yields satisfactory results.**

Index Terms—**Command and Control Systems, Decision Support System, Vessel Navigation, Route Optimization, Vessel Interdiction, Dijkstra's Algorithm.**

I. Introduction

Threats in the marine domain involving social, political or economic affairs may cause conflicts in local areas, and even in international waters. When an intervention is needed because of an immediate threat, operators must make decisions based on the available information. In these cases, a fast intervention may guarantee a high rate of success. In addition, high safety is desired in any operation.

Command and Control (C2) systems helps the commander for planning, directing and controlling operations [1]. Nonetheless, the commander is usually assisted by software programs so that the final decisions are taken according to quality information. In this regard, several technologies are used to obtain quality information and make a good decision. For instance, path-planning is used in autonomous underwater vehicles (AUVs) to guide them towards a goal according to specific requirements as shown in [2]. Then, AUVs may sample the maritime domain in order to characterize an area of interest (AOI) by means of oceanographic measurements. Other multi-objective scenarios have been analyzed to generate routes through weather routing so that travel time or fuel consumption is minimized as discussed in [3]. Similarly, this paper will consider a path-planning technique to support decision-making, aiming to add new features to C2 systems.

The authors present an innovative Decision Support System (DSS) to support C2 operators. This system is aimed to increase the rate of success in a maritime interdiction through the use of a navigation model. Specifically, the system provides the best location where an interdiction can be carried out under diverse meteorological and oceanographic (METOC) conditions. Therefore, it would enhance the security in the maritime domain, such as in unidentified threats or the protection of ports or territorial waters. As far as the authors know, the open literature does not describe similar systems, besides the work developed at NATO STO Centre for Maritime Research and Experimentation (CMRE) on this topic [4].

The paper is structured as follows. Section II describes the methodology and architecture of the MVIS. Then, a case study is presented in Section III and the results are analyzed. Finally, conclusions are drawn in Section IV.

II. MVIS System description

METOC-driven Vessel Interdiction System [4] comes up as an architecture designed to support decision-making when and where an interdiction operation would occur. The initial scenario contains a main vessel, represented by the Blue Force, attempting to interdict a hazardous vessel, marked as a Red Force, within the Mediterranean Sea as area of interest. A set of N points, belonging to the discretized Red Force path sampled at the time resolution of the METOC forecasts minimum resolution, becomes the interdiction locations to be analyzed. Then, for each interdiction location MVIS yields an optimal route that allows the Blue Force vessel to sail under the safest METOC conditions and/or taking the fastest track towards the current objective. As a final step, the system generates a ranking of the interdiction locations to aid the operator in the selection.

The scheme integrates three stages: the METOC information database, that provides the METOC forecasts used in the system; the routing algorithm, which calculates the optimal routes to each interdiction location; and the decision-making stage, which yields the final ranking of interdiction locations.

A. METOC forecast database

The forecasts of the METOC variables are provided by a numerical ocean model (NOM) of the Mediterranean Sea [5]. In particular, the WaveWatchIII model, developed by the National Oceanic and Atmospheric Administration (NOAA) [6], is used. To drive the simulations, the WaveWatchIII model requires wind forcing provided at 10-m height over the sea surface, which are obtained from the non-hydrostatic mesoscale Weather Research and Forecasting - Advanced Research WRF model (WRF-ARW) [7]. The Climate Forecast System Reanalysis (CFSR) [8] database provides the initial and boundary conditions for atmospheric simulations with the WRF model. The NOM is characterized by a domain composed of 336×180 cells distributed over a regular Cartesian grid. Latitude resolution is 0.09° ($\Delta_{lat} \simeq 10km, \sim 6.2nmi$), and longitude resolution is 0.1273° ($\Delta_{lon} \simeq 14km, \sim 8.7nmi$ at $45°N$). Latitude and longitude resolutions define an average spatial resolution of about 12 km. The Mediterranean basin is delimited by the coordinates $30°N$ and $46.11°N$ in latitude; and $-5.9°E$ and $36.75°E$ in longitude. Time resolution corresponds to 1 hour and the forecasts simulate up to 72 hours, starting at midnight (00:00:00 UTC). The first 24 hours will be used in MVIS since accuracy decreases as forecast evolves and daily forecasts are available.

From this METOC forecast database, the following variables are considered:

- Significant wave height: H_s [m]
- Mean wave period: T_m [s]
- Mean wave length: λ_m [m]
- 10-meter wind speed and direction: u_{10} [m/s] and ϕ_{10} [rad], respectively. The reference direction is North.
- Bathymetry: d [m]

B. Navigation model and routing algorithm

This stage of the MVIS architecture performs the optimization process by means of a navigation model. Restricted through specific constraints, the minimum cost routes, namely the best routes, are found out by Dijkstra's algorithm [9] that acts as path planning or routing algorithm. For this task, a navigation model computes the cost maps that lead the algorithm. Then, one optimal route is computed for each interdiction location of the N-length Red Force vessel path.

The optimization starts from the Blue Force vessel initial location and finds out the best route towards each interdiction location. A cost must be defined since Dijkstra's algorithm has to discover minimum cost solutions. Besides, the objective is to interdict the Red Force vessel at the earliest opportunity and in the best METOC conditions. Therefore the travel time is chosen. Hence, the cost maps are composed of a matrix where each cell corresponds to the travel time in the current cell. In turn, cost maps change dynamically every time resolution units (1 hour in this case) depending on the METOC forecasts. Note that when the Blue Force vessel travels, the METOC forecasts are selected according to the corresponding time.

The development of a navigation model allows computing the cells' travel time. In particular, the cell's travel time is defined as the distance sailed by the Blue Force vessel in a cell divided by its real current speed, v_r. Mathematically, the process is as follows.

At first, the distance surfed by a vessel over one wave, d_w, is given by the rectification of this curve (i.e. arc length of the sea wave). Besides, if a sea wave length is less than the Blue Force vessel length, b_l, flat sea waves are considered. (1) provides the mathematical definition of d_w.

$$d_w = \begin{cases} \lambda_m, & \text{if } \lambda_m < b_l. \\ \int_0^{\lambda_m} \sqrt{1 + f'(x)^2}\,\mathrm{d}x, & \text{otherwise.} \end{cases} \tag{1}$$

Where $f'(x)$ represents the first derivative of $f(x)$, and $f(x)$ is the function that models the wave.

In particular, to simplify the calculus, a sinusoidal function of amplitude H_s and period λ_m models sea waves as indicated in (2).

$$f(x) = \frac{H_s}{2} \cos\left(\frac{2\pi}{\lambda_m} x\right), \tag{2}$$

where x represents the spatial dimension of a wave.

The number of sea waves fitting into a resolution cell, N_w, are quantified by $N_w = \Delta_{lat}/\lambda_m$ where Δ_{lat} is the latitudinal cell range.

So, the distance surfed by a vessel within a cell, d_{cell}, is obtained by multiplying the number of sea waves within a cell, N_w, by the rectification of the sea wave, d_w. This is $d_{cell} = N_w \cdot d_w$.

The previous d_{cell} formula measures the sea wave distance in a cell in case of performing a vertical (North/South) movement; however, the Blue Force vessel may move vertically, horizontally (East/West) or diagonally. Therefore, since the resolutions for latitude and longitude are different, a correction must be done. This correction assures a new distance, d'_{cell}, which will be used in next steps.

$$d'_{cell} = \begin{cases} d_{cell} \cdot 1 & \text{when vertical} \\ d_{cell} \cdot (\Delta_{lon}/\Delta_{lat}) & \text{when horizontal} \\ d_{cell} \cdot \sqrt{1 + (\Delta_{lon}/\Delta_{lat})^2} & \text{when diagonal} \end{cases} \tag{3}$$

This step computes the distance surfed by the Blue Force vessel in a cell.

The real Blue Force speed in the current cell, v_r, depends on the constant and initially fixed Blue Force vessel speed, v_n, but also on the down winds in that cell. These last are considered since they may help the vessel to reach the goal faster. Thus, v_r is expressed as $v_r = f(v_n, u_{10}, \phi_{10})$, where u_{10} and ϕ_{10} belong to the wind components of the cell.

More in detail, the wind components affect directly the vessel, and so v_r, according to its navigation direction. It defines the apparent wind. As already explain in Section II-A, u_{10} and ϕ_{10} give wind measurements at 10 meters high over the sea surface. However, the wind force affects the vessel near the sea surface, therefore the shear velocity [10], u_*, arises. (4) shows linear relationship between shear velocity and the wind speed from the METOC database.

$$u_* = \sqrt{C_D} u_{10}, \tag{4}$$

where C_D is the drag coefficient of the sea surface (see definition in [11]).

Apparent wind is computed as the projection of the shear velocity over v_n, taking North direction as reference. Then it is added up to v_n. Taking into account these effects, v_r is determined as

$$v_r = v_n + u_* \cdot cos\left(\phi_b - \phi_*\right), \tag{5}$$

where ϕ_b indicates the navigation direction of the Blue Force vessel and ϕ_* represents the wind direction of the shear velocity, assumed equal as ϕ_{10}.

Finally, a cell's travel time is computed as

$$t_{cell} = d'_{cell}/v_r. \tag{6}$$

The previous process determines the travel time for every cell of the cost maps. Now Dijkstra's algorithm is able to discover optimal routes to the N interdiction locations. The N interdiction points are joined through the vector **I**.

$$\mathbf{I} = \left\{I_1, I_2, \cdots, I_N\right\}, \tag{7}$$

where $I_i = \left\{Lat_i, Lon_i\right\}, i = 1, \cdots, N.$

Moreover, the proposed optimal routes for the N interdiction locations are grouped in vector **R** as

$$\mathbf{R} = \left\{r_1, r_2, \cdots, r_N\right\} \tag{8}$$

C. Decision-making stage

After computing the optimal routes for each prospective interdiction location, the aim of this stage is to provide an operator the ability to select the interdiction location with the safest environmental conditions. Considering the set of N interdiction locations found in (7), an assessment is done to classify the solutions according to the environmental risk. The risk of the N locations is sorted into a ranking. In order to sort and compare, the risk is provided through an objective value or metric. Since sinusoidal waves were assumed, the energy flux [12], E, is chosen. It represents the wildness of the sea state in the chosen location, and is expressed as

$$E_i[kW/m] = \frac{1}{8}\rho g H_{s,i}^2 C_{g,i}/1000, \tag{9}$$

where i indicates the interdiction location, g represents the acceleration by gravity and ρ represents the sea water density -supposed at 1020 kg m^{-3}. C_g is the group velocity, which differs for deep, transitional and shallow waters. However, the equation summarized in [13] takes into account every bathymetry, employing the METOC variables explained in Section II-A. The physical meaning of the metric reveals the wave power in kW per meter of wavefront length. The lower the energy flux, the lower sea state. Based on this, this stage searches for the lowest metric.

Every E_i is stored in a vector **E** as:

$$\mathbf{E} = \left\{E_1, E_2, \cdots, E_N\right\}. \tag{10}$$

At this point, the N interdiction locations are ranked. First, the travel time of the Blue Force vessel, t_{BV}, and Red Force vessel, t_{RV}, is compared at every interdiction location: if the Blue Force vessel arrives before than the Red Force vessel, the point is selected as reachable and colored in green; on the contrary, the point is considered as unreachable and marked in a red color. Doubtful points (difference of a time resolution unit in the vessels' arrival) are considered as marginal points and, generally, since they are ambiguous, the operator decides whether removing them.

Taking this into account, an auxiliary vector, **A**, is created according to the reachability criteria, so that the reachable locations are kept and the marginal and unreachable locations are removed. Therefore N_f points remain, where $N_f \leq N$. Vector **A** is defined as

$$\mathbf{A} = \left\{E_1, E_2, \cdots, E_{N_f}\right\} \tag{11}$$

where its elements belong to reachable interdiction locations.

Three new vectors, **R'**, **I'** and **E'**, are created from the set of **R**, **I** and **A**. Vector **E'** is increasingly ordered according to the values stored in vector **A**:

$$\begin{gathered}\mathbf{E'} = \left\{E'_1, E'_2, \cdots, E'_{N_f}\right\} \\ \text{where } E'_1 = min\left\{A\right\} < \cdots < E'_{N_f} = max\left\{A\right\}.\end{gathered} \tag{12}$$

Vector **E'** is ranked and, consequently, vectors **I'** and **R'** are rearranged following the positions of the **E'** values. The ordered valid solutions of interdiction locations are kept in **I'**.

$$\mathbf{I'} = \left\{I'_1, I'_2, \cdots, I'_{N_f}\right\}, \tag{13}$$

where the first element, I'_1, belongs to the best case (i.e. safest METOC conditions) with the lowest risk metric (E'_1). On the opposite side, the last element, I'_{N_f}, represents the worst case holding the highest risk metric (E'_{N_f}).

And, finally, vector **R'** redefines as:

$$\mathbf{R'} = \left\{r'_1, r'_2, \cdots, r'_{N_f}\right\}, \tag{14}$$

where $r'_1 = \left\{r_i \mid min\left\{E'\right\}, i = 1, \cdots, N_f\right\}$ and $r'_{N_f} = \left\{r_i \mid max\left\{E'\right\}, i = 1, \cdots, N_f\right\}$.

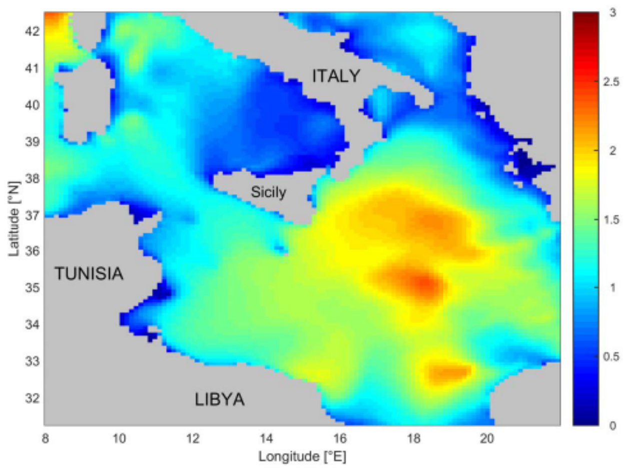

Figure 1. METOC variable: Forecast for H_s [m] on the 24^{th} April 2012 00:00:00 UTC +11h

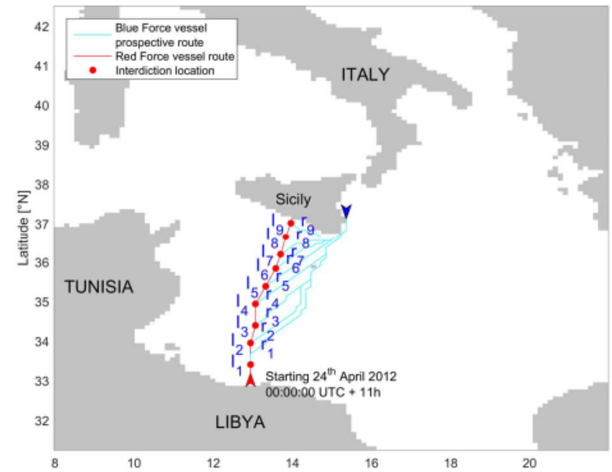

Figure 2. Prospective routes (r_i) and interdiction locations (I_i) of the operation. Blue Force vessel sails at 25 kn from Catania, Italy. Red Force vessel cruises at 20 kn from South to North, starting in the coast of Libya.

III. Results

This Section is focused on the analysis of a case study in order to show the MVIS performance. The case study considers an interdiction scenario occurring under several sea states, corresponding to diverse METOC conditions. In particular, MVIS will lead the Blue Force vessel towards the Red Force vessel, avoiding strong METOC conditions produced by a storm in the selected AOI. According to the Douglas scale provided by the World Meteorological Organization (WMO) [14], smooth, slight and moderate sea states will take part in the scenario, which belongs to H_s from 0 m up to 2.5 m.

The scenario takes place in the Ionian Sea, bounded by the south of Italy, west of Greece and the coast of Libya, within the Mediterranean Sea. In particular, the geographical points that delimits the AOI goes from $[7.97897°E, 31.26°N]$ to $[21.98527°E, 42.51°N]$. The interdiction operation starts with METOC forecasts on the 24th April 2012 00:00:00 UTC +11h. Blue Force vessel is located at $[15.23678°E, 37.47°N]$. Its speed is fixed to 25 knots, $v_n = 25kn$, and a length, b_l, equal to 25 meters is supposed. Red Force vessel speed is set to 20 knots and moves from $[12.94484°E, 32.97°N]$ to $[13.96348°E, 37.02°N]$. From the Red Force vessel trajectory, a total of $N = 9$ interdiction locations are obtained from the initial Red Force predicted route.

Fig. 1 shows an image of the H_s at the beginning of the operation. A maximum value of $H_s = 2.5$ meters characterizes the scenario. At this point, the objective of the METOC-driven routing algorithm lies on finding the minimum cost route for each interdiction location and generate N prospective routes.

Once the Dijkstra's algorithm discovers the optimal routes, vector **R** is defined as $\mathbf{R} = \{r_1, r_2, r_3, r_4, r_5, r_6, r_7, r_8, r_9\}$, where r_i belongs to each I_i. In turn, vector **I** holds the set of interdiction location in $\mathbf{I} = \{I_1, I_2, I_3, I_4, I_5, I_6, I_7, I_8, I_9\}$. Fig. 2 illustrates the prospective optimal routes of vector **R** and the interdiction locations of vector **I**. Next, for all the interdiction locations I_i, the environmental risk metric E_i is computed. Therefore, vector **E** becomes

$$\mathbf{E} = \{0.56, 0.74, 0.92, 1.16, 1.44, 1.48, 1.34, 1.31, 1.14\}\,. \tag{15}$$

Travel times t_{BV} and t_{RV}, obtained from the optimization stage, are compared as explain in Section II-C. If $t_{BV} < t_{RV}$ (i.e. Blue Force reaches an interdiction location before than the Red Force) in a specific I_i, then it is considered as reachable location. Otherwise, it is marked as unreachable. This particular case study does not present ambiguous locations. Fig. 3 shows the reachable and unreachable locations.

Unreachable locations, I_1, I_2, I_3 and I_4, are removed and, so, $N_f = 5$. The remaining set of reachable locations yields the auxiliary vector **A**, where its elements are the E_i values of I_5, I_6, I_7, I_8 and I_9. So,

$$\mathbf{A} = \{E_5, E_6, E_7, E_8, E_9\} = \{1.44, 1.48, 1.34, 1.31, 1.14\}\,. \tag{16}$$

The order is managed according to their metric values. Hence, vector **E'** turns into

$$\begin{aligned}\mathbf{E'} &= \{E'_1, E'_2, E'_3, E'_4, E'_5\} = \{E_9, E_8, E_7, E_5, E_6\} \\ &= \{1.14, 1.31, 1.34, 1.44, 1.48\}\,.\end{aligned} \tag{17}$$

As a result, vector **I'** is arranged as

$$\mathbf{I'} = \{I'_1, I'_2, I'_3, I'_4, I'_5\} = \{I_9, I_8, I_7, I_5, I_6\}\,. \tag{18}$$

Similarly, the sorted optimal routes is reflected in vector **R'**. In particular,

$$\mathbf{R'} = \{r'_1, r'_2, r'_3, r'_4, r'_5\} = \{r_9, r_8, r_7, r_5, r_6\}\,. \tag{19}$$

Finally, MVIS produces a table where the case study is summarized (see Table I). This table provides the operator a fast way to identify the option that fits better to the current

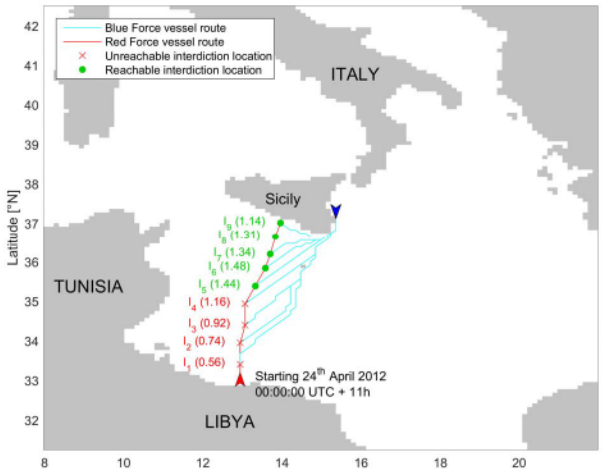

Figure 3. Assessment of the interdiction operation. Blue Force vessel sails at 25 kn. Red Force vessel cruises at 20 kn from South to North. Reachable interdiction locations colored in green; unreachable interdiction locations colored in red. Risk metric value, E_i, is provided in brackets for each I_i, $i = 1...9$.

Table I
RESULTS OF THE INTERDICTION OPERATION WHERE BLUE FORCE VESSEL SAILS AT 25 KN FROM CATANIA, ITALY, AND RED FORCE VESSEL CRUISES AT 20 KN STARTING IN THE COAST OF LIBYA. COLUMNS IDENTIFY THE INTERDICTION LOCATION I_i, ITS GEOGRAPHIC POSITION, THE BLUE FORCE TRAVEL TIME t_{BV}, THE RED FORCE TRAVEL TIME t_{RV}, RISK METRIC E_i AND THE SORTED METRIC E'_i.

I	[Lon, Lat] [$°E$, $°N$]	t_{BV} [h]	t_{RV} [h]	Metric (E_i)	E'_i
I_1	[12.9448, 33.42]	10 h	1 h	0.56 (E_1)	x[1]
I_2	[12.9448, 33.96]	8 h	2 h	0.74 (E_2)	x[1]
I_3	[13.0722, 34.41]	7 h	3 h	0.92 (E_3)	x[1]
I_4	[13.0722, 34.95]	6 h	4 h	1.16 (E_4)	x[1]
I_5	[13.3268, 35.40]	5 h	5 h	1.44 (E_5)	E'_4
I_6	[13.5815, 35.85]	5 h	6 h	1.48 (E_6)	E'_5
I_7	[13.7088, 36.21]	4 h	7 h	1.34 (E_7)	E'_3
I_8	[13.8361, 36.66]	4 h	8 h	1.31 (E_8)	E'_2
I_9	[13.9635, 37.02]	4 h	9 h	1.14 (E_9)	E'_1

[1]Interdiction is not possible

requirements, i.e. selection of the interdiction location with the safest conditions.

MVIS yields I_9 as best solution since it presents the safest METOC conditions for interdiction according to Table I, converting it into the most conservative option.

A. Limitations derived from the case study

The above case study depicts the general performance of MVIS but also discloses two limitations affecting the decision-making stage.

First, the navigation model of the routing algorithm assumes constant speed for the Blue Force to lead it to the goal. As well, Red Force travel time is computed by means of a fixed speed. However, sea waves produce variations in the speed that are difficult to model and induce uncertainty, reducing the accuracy of MVIS.

Second, once the optimal routes are computed, the decision-making process could remove all the interdiction locations from the solutions due to not finding out any reachable point and, therefore, MVIS does not propose any interdiction location. Then, whenever possible, a relocation of the Blue Force vessel or the choice of an asset located in other geographic location should be used.

IV. CONCLUSIONS

MVIS introduces a new concept of support in decision-making for C2 systems. In an interdiction operation scenario, this scheme contributes to a fast assessment of all the possible interdiction locations, allowing the operator to make a quick decision based on trustworthy information.

The analysis of the previous case study lets expose up to four main conclusions. First, MVIS provides an optimal route, if exists, for every interdiction location. Second, pathfinding is not dependent on the METOC conditions in any given scenario. Third, the safety of the operation is maximized since MVIS yields as the best solution the safest interdiction location in terms of METOC conditions. Uncertainty is avoided by removing the marginal and unreachable locations from the solution space. And four, the last choice is made by the user/operator. Besides, if there are two different departure points of the Blue Force vessel available, the operator could decide the most suitable option according to the analysis of both cases.

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Title

METOC-driven vessel interdiction system (MVIS): Supporting decision making in Command and Control (C2) systems

Abstract

This paper presents a decision support system (DSS) to help Command and Control (C2) operators. Hereby, the METOC-driven vessel interdiction system (MVIS) is presented. It is aimed to help the decision-making process in case of interdiction operations so that the success rate increases. In particular, MVIS yields the best location along a predicted path to interdict a vessel in the best meteorological and oceanographic (METOC) conditions and/or taking the fastest track. The system scheme includes two main processing stages: the routing algorithm and the decision-making stage. The routing algorithm finds out the minimum cost-optimal-routes through an optimization algorithm to the predicted interdiction locations. The algorithm is guided by means of a navigation model that employs METOC variables, such as the significant wave height or the wind. A numerical ocean model (NOM) provides the METOC forecasts. The decision-making stage arranges the proposed solutions according to a risk metric, which is computed by an objective function. The best solution corresponds to the lowest metric. As a final step, the ranking of solutions is visually presented to the operator. To illustrate the MVIS performance, a case study within the Mediterranean Sea is developed that yields satisfactory results

Keywords

Command and control systems, decision support system, vessel navigation, route optimization, vessel interdiction, Dijkstra's algorithm

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