STATIC MARITIME ENVIROMENT REPRESENTATION OF ELECTRONIC NAVIGATIONAL CHARTS IN GLOBAL PATH PLANNING

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Keywords

global path planning, discrete planning algorithms, electronic navigational charts

Abstract

In past years, numerous global path planning methods have been researched and applied in maritime surface navigation. Regardless of intended usage for either decision-support in crewed, or autonomous vessel navigation, path planning should generate a safe and efficient route. However, prior to route generation, static maritime environment representation must be created first. Whether it is transformed in to discrete or continuous form, common approach is to use Electronic Navigational Charts (ENCs) as a basis for maritime environment representation. Nevertheless its origins, ENCs still adhere to inherited data generalizations and simplifications to be comprehensible for human navigators. This leads to limitations when considering path planning and spatial resolution at different chart scales. Furthermore, when generating the representation and path, uncertainty must be considered since the quality and accuracy of chart data varies. Although these topics have been addressed separately in their respective domains, their relations have not been researched in detail. The aim of the proposed paper is the review of electronic navigational charts, environment representation and common global path planning approaches' relations. Forthcoming standards and technologies, such as usage of high-density charts, are presented and discussed as well.

1. INTRODUCTION

Safe and efficient navigation of the ship is based, among other things, on appropriate path planning. In the planning process, navigational requirements, constraints, static and dynamic conditions are assessed using the data from a variety of sources. The characteristics of the ship and the area, expected traffic density and weather conditions, route efficiency are just some of the factors determining the final content of the voyage plan (1). Traditionally done by on-board navigators, the methods of voyage planning are elaborated and extensively presented in various sources: international regulations, circulars and recommendations, procedures of shipping companies and professional literature. Uniformity and objectivity in the approach are the objectives of maritime education standards, determining the appropriate skills and competences of the navigators. Nevertheless, partial subjectivity is present in the voyage planning, conditioned by the proficiency, experience or by the vagueness of the definitions. Procedure improvement, introduction of advanced Decision Support Systems (DSS) and ultimately fully autonomous navigation systems should be a path towards reduction of subjectivity. Therefore, it is necessary to mention the recent completion of Electronic Chart Display and Information System (ECDIS) implementation on ships (2). Tentatively speaking, this completed the transition from traditional or mixed approaches of voyage planning to technologically integrated approaches. The upcoming stages of voyage planning development are followed by the implementation of new standards, the use of high-density data and various levels of automated route planning. This applies to vessels which will still be manned depending on the level of autonomy (3). The tasks and characteristics of planning will change, with a gradual transformation in the human involvement level during planning phases. However, the immediate context and objective of the planning will remain the same, at least until humans will continue to approve the plan: *Determine a safe vessel path based on a human-legible limited view of reality in the form of an Electronic Navigational Chart (ENC)*. Therefore, there are several basic elements to consider accomplishing the stated objective. It is necessary to consider the limitations of ENCs including the methods by which the data were collected, their accuracy and confidence and finally generalization. Furthermore, ships characteristics must be considered as well with available and forthcoming solutions in supervised or fully autonomous path planning. Accordingly, there are considerable research efforts on voyage planning (4), ENCs (5), navigational characteristics of the ship (6) and path planning (7).

Besides maritime research fields and other branches of transport, path planning is researched in robotics, autonomous vehicles, and computer technologies. In the context of movement, path planning includes defining the vehicle model, i.e., the vessel in the presentation of the physical space in which it is located. If we include the time of movement along the path, we determine the trajectory of the vessel as well. When the environment is fully known and determined and the obstacles are stationary, path planning is static and time-invariant (8). Therefore, we can define global path planning (GPP) in which path is planned in a fully known static environment (9). Unlike global, local path planning (LPP) deals with avoidance of nearby static or dynamic obstacles while underway. Among numerous methods, discrete graph search based on graph theory is a common approach in path planning.

To search the graph, it is necessary to discretize the space for example, in form of grids, meshes or polygons. Resulting free space, based on method used, can consist of simpler regions called cells. Depending on the algorithm applied and weight factors, the most favorable path is determined, that is, a solution with a minimum distance or weight. The generated path usually contains a larger number of unnecessary vertices or waypoints which must be reduced. While the waypoints and associated courses between them may correspond to the limits and criteria set, they do not necessarily correspond to the ship's maneuvering characteristics or path planning requirements. Thus, the obtained paths need to be adjusted. On board, the navigator adjusts the position of the waypoints and radius of the ship's turning circle according to the ship's known maneuverability and if available, conspicuous navigational features. In the application of algorithms, realistic paths can be created by smoothing curves and approximations of mathematical functions (10). Therefore, to properly model the environment and apply the path algorithm on ENC structure, features and shortcomings must be known.

There are several standards set by the International Hydrographic Organization (IHO) defining the ENCs. The content, structure, and specifications of ENCs is specified in IHO S-57 standard harmonized with ECDIS performance standards. ENC content stored in object-oriented database format with 200 classes of spatial objects and 185 classes of feature objects describe the features and position of real objects in the maritime environment. Furthermore, the ENC content is separated from presentation and defined in IHO S-52 standard (11). Several challenges arise when using ENCs as basis for environment representation. Since it approximates the real-world environment, large volume of data must be collected, transformed, and reduced to be understandable to humans. This, along with limitations of devices used for data acquisition and production results in several shortcomings. Charts and objects have intrinsic hydrographic uncertainty (12), sounding and isobaths are generalized and conform to constraints to be legible (13). Furthermore, using IHO S-57 format standalone or combined with ever-increasing volumes of datasets and formats inside and outside of the ECDIS environment is a challenge on its own. However, the forthcoming IHO S-100 products resolve some of these challenges opening numerous possibilities for a wider userbase (14).

As presented, ENCs, environment models and path planning are well researched in various scientific disciplines. The level of consideration is often consistent with their significance in their origin research field. However, past considerations of the interrelationship between environment modeling, ENCs and GPP, directs to more research towards unified interpretation. Therefore, the aim of this paper is to present the overview of static environment models based on ENCs used in GPP. The rest of the paper is organized as follows: Section 2 summarizes important work on GPP, ENCs and static environment representation. Section 3 presents the results of survey on the GPP approaches using the ENCs and static environment representation. Section 4 discusses the findings with current and forthcoming approaches. Section 5 contains conclusions and recommendations for future research.

2. GLOBAL PATH PLANING AND STATIC MARITIME ENVIROMENT

To assess the relations between maritime static environment representation and the GPP methods, an overview of common GPP methods and algorithms is presented in the following subchapters. Brief overview of IHO standards, ENC features follows in the subsequent subchapter. In the final subchapter, approaches to environment modelling, their features, advantages and disadvantages are described.

2.1. GLOBAL PATH PLANNING

There are numerous approaches used in path planning, which we can generally divide into classic, advanced and hybrid (15). In classic approaches, used often for global path planning, a model of environment is usually created and then the optimal path determined. Advanced approaches are often used to avoid dynamic objects and local planning and frequently do not require an environment model. Hybrid approaches combine algorithms and are used for both global and local planning (15), (16). The first approach provides optimal solutions suitable for cases that require fewer degrees of freedom and includes deterministic algorithms with heuristics (17). From this group of algorithms, the A* algorithm and its variants are very often used. Optimization approaches also differ. If only the shortest path, smoothness or safety is optimized, single-objective optimization is applied. If the path planning problem is expressed as a problem for all three of the above objectives (18), multi-objective optimization approaches (19), (20) are often applied. To finish, if we consider motion and path planning, then approaches can be broadly divided into graph search, sampling, curve interpolation and numerical optimization (21).

According to GPP methods from robotics, we differentiate roadmap, space decomposition and potential fields. In the first two approaches, the problem of determining the path is reduced to graph search, which is preceded by determining connectivity in free space. Roadmap methods have the advantage that they are simpler to implement in 2D or 3D configuration space, or state space. By decomposition methods, free space is divided into smaller areas, that is, cells. Methods can be exact and give complete or approximative solutions or approximatively complete solutions at the given resolution. Finally, potential field methods use a potential field gradient in proximity of an object, and not for the free space. This makes them efficient, however trapping in the local minima may occur (22). In addition to the above methodology, the expanded systematization of path planning algorithms includes limitations of movement, the need for space modeling, mode (online/offline) and whether algorithms are deterministic or probabilistic (23).

Considering the general evaluation criteria of path planning algorithms, they can be expressed in terms of optimality or completeness, efficiency, and insensitivity to environmental complexity (24). More detailed metrics of the GPP algorithms can include mean execution time, relative standard deviation of execution time, mean length of path, relative standard deviation of the length of the path and smoothness of the path (25). Further, if we consider the optimality of path planning, then this can be the shortest path or route, time optimal path, path with the lowest energy consumption, optimal smoothness, or minimum risk (26). If we consider similarity criteria between paths, then the shape similarity can be compared using Fréchet or Hausdorff distance (27), while for the trajectory similarity time-warping methods are used as well (28).

2.2. ELECTRONIC NAVIGATIONAL CHARTS

The IHO S-57 standard was officially adopted in the 1992 and used almost exclusively for encoding of ENCs and used in ECDIS. The limitations are that it was primarily developed for ECDIS use and it has inflexible maintenance regime. The standard is frozen, and the structure does not support advanced features such as gridded bathymetry. Furthermore, the data model is embedded within the file format thus limiting flexibility in usage (28). The ENCs have several challenges in potential application for path planning such as data sources, format usage or hydrographic uncertainty. The data can be from older surveys with lower accuracy, even in coastal areas and of high maritime traffic (30) which must be accounted for in path planning. Solutions to format challenges can be in part solved with publicly available format translations (31) where ENCs are converted to common formats such as shapefiles (SHP) or geodatabase file collections (GDB) for use in Geographic Information Systems (GIS) applications. Furthermore, there are open-source libraries capable of format translation (32), even free navigational software (33), however with limitations in context of path planning.

Figure 1. Electronic Navigational Chart (ENC)

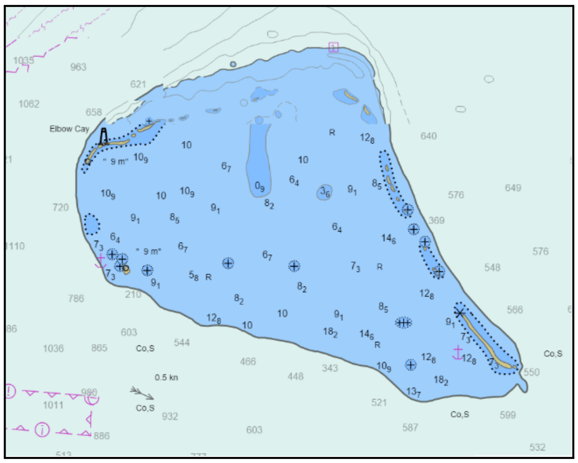
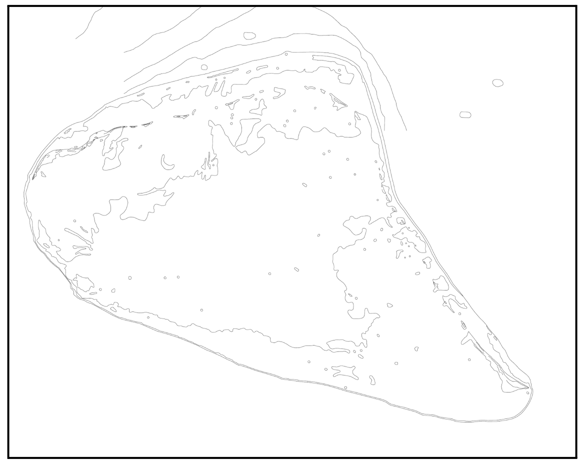


Figure 2. ENC Depth contour object-DEPCTN



Source: Adapted by the authors from National Oceanic and Atmospheric Administration (NOAA) US410121 ENC: Approach to Cay Sal Bank.

There are several considerations that arise when using and interpreting data from ENCs when using GPP algorithms. The first is the hydrographic uncertainty of the chart data. The uncertainty arises from the data collection methods, the devices used and their limitations. From the data, models of environment are created in which data often must be interpolated because of no or limited data availability for a whole or specific area. Further, given the methods of interpolation and variability of the data used, the model itself has uncertainty. To represent and interpret uncertainty, ENCs contain a metadata layer (M_QUAL Zones Of Confidence–CATZOC). Although it describes how the data was collected, it does not represent the actual accuracy or uncertainty of the representation of e.g., the bottom in the navigation area is (34), (12). The second challenge is the generalization of the ENC presentation. It is defined in constraint terms of legibility, safety, topology, and morphology, which ensures appropriate interpretation of data, and general safety for navigation. These constraints are sometimes opposed, so a compromise must be made, especially at different chart scales (35). As an example, an ENC with basic layers and objects such as depth contours, soundings or land features is presented in Figure 1. Furthermore, the single ENC depth contour object (DEPCTN) is visible in Figure 2., representing the layered approach to data representation. The third challenge is to use the available ENC layers in GPP. In a variety of path planning approaches, usage of ENC depth data or DEPARE object is just generally stated. However, other objects are available under the group of geographic objects defined in IHO S-52 standard (34). The last challenge for the ENC usage is for a variety of research or application approaches. ENCs can be presented in whole or partially, but there is no commercial or open-source platform or environment for which individual elements of research interests related to ENCs or even ECDIS could be fully and interactively considered. This applies to data visualization, geospatial analytics, path planning, autonomous vessels, or simulations (36). This observation does not address navigational simulators which are used for training and other research topics because of their mostly closed-source nature for experimentation and research on GPP, static environment and ENCs, which is the topic of the paper.

To handle the S-57 and other related standards complexities and challenges, in 2005 IHO proposed the

S-100 products (S-101 to S-199). The first edition was published in 2010 and it has been updated four times since. From the IHO S-100 products S-101 is Electronic Navigational Chart Product Specification which includes feature and portrayal catalogue, complex attributes, rich geometry, and information types. It has the capability to superimpose layers with advanced and dynamic display of other S-100 products such as high-resolution bathymetry or dynamic environmental data and be used for intelligent navigation in ECDIS (31). To overcome S-57 limitations the S-100 product family is mostly compatible with international ISO 19100 Geographic Information Standards. This facilitates exchange with and usage of multitude of data sources and formats. The S-101 has dynamic feature and portrayal catalogue. The relations between features, attributes and enumerations are defined within same single feature catalogue, which is machine-readable, simplifying updates for stakeholders [38]. Final consideration on ENCs and forthcoming standards is the usage of high-density bathymetric data. Since mean depth contours are 2, 5, 10, 15, 20- and 30-meter interval, there is a practical limitation when used as safety margin and alarm states for example the ship's draught. High Density bathymetric ENCs (HDbENC) or HD ENCs were developed and are currently actively tested. They have denser depth contours of 1 m or closer, large compilation scales (larger than 1:4000) and require frequent updates since they cover dredged area or areas of dense traffic and narrow waterways (39).

2.3. ENVIROMENT REPRESENTATION

To use GPP methods for graph search, the space needs to be conveniently discretized. For this purpose, regular and irregular meshes, polygons or graphs are used. Regular meshes are easy to generate, however require high resolution to create a sufficiently realistic representation of the navigational area. Irregular meshes represent a more accurate representation, however require a greater number of parameters for creation (5). In addition to meshes, space can be converted to a graph using quadtrees, Voronoi diagrams, or visibility graphs (40). An example of representations Delaunay triangulation created from ENC soundings is depicted in Figure 3., while a regular grid superimposed on land areas and depth contours is shown in Figure 4.

Figure 3. Delaunay triangulation created from ENC soundings

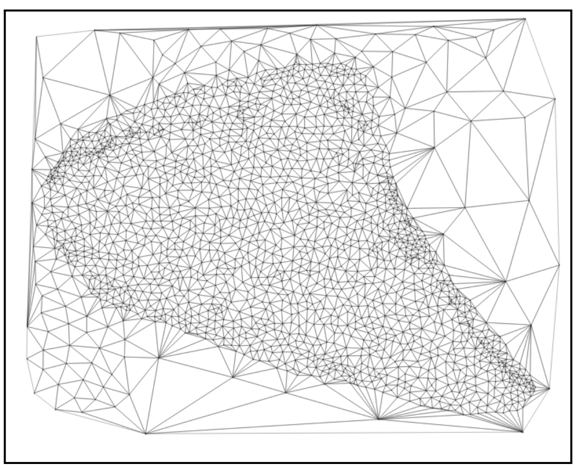
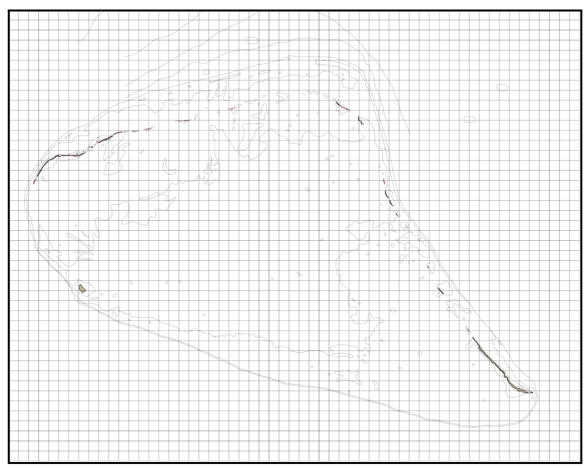


Figure 4. Regular grid superimposed over ENC



Source: The authors. Created from National Oceanic and Atmospheric Administration (NOAA) US410121 ENC data.

Every presented approach has its own advantages and shortcomings. Regular grids besides implementation and update simplicity have same number of nodes regardless of number of obstacles, common in form of squares, triangles, or hexagons although they are less accurate for modelling of obstacles. Furthermore, issues with memory overhead are present in higher resolutions thus increasing computation time, memory, or other resource usage. Irregular grids such as quadtrees divide the space in four squares and continue the process producing smaller and smaller squares until every square has an obstacle inside. The advantage of this method is faster graph search and less memory usage than regular grids. The disadvantage is the possibility of path quality reduction and reduced or even loss of applicability in high density of obstacles. Navigation meshes and visibility graphs have similarities, although meshes are less complex. In visibility graphs start and end nodes are connected either with shortest path or as tangents to obstacle vertices. If they are combined with Dijkstra's or A* algorithms they provide an optimal solution, however feasible only in 2D space. The Voronoi diagram creates equally distanced lines from obstacles such as polygons. The advantage is the safe distance from obstacles, on the expense of optimality, which is not a shortcoming if the shortest path is not the primary objective (23). As presented, environmental modelling decision is therefore a crucial step in consideration of method or algorithm. The concept of environmental modelling is further elaborated in terms of configuration space.

In general, configuration space (C-space) emerged from robotics and motion planning that transforms dimensional object in the classic approaches into a point. The obstacles are mapped, and the object motion problem is transformed in path planning of a point (22). Further, the C-space mapping representations schemes can be broadly categorized as boundary, divide-and-classify and hybrid (41). As such, these representations are the foundation of the numerous path planning algorithms in static environments. A comparison of different configuration spaces for path planning under combinatorial method can be found in (42). The authors stated that in combinatorial path planning using visibility graphs shortest path without local minima was obtained, while satisfying completeness and minimum travelled path criteria. The simple implementation and computation increase disadvantage was stated as well. For the Voronoi diagram representation, the stated advantage was minimum computation time, global optimal solution, completeness, and avoidance of local minima. However, the shortest path could not be created due to basic property of the diagram (obstacle equidistance) thus reflecting in high possibility of energy or distance cost. Cell decomposition guarantees completeness, and local minima avoidance. However, the path quality is dependent on the cell size which reflects in computation increase with higher resolution. Artificial potential field method shortcoming is that it is influenced and directed by local obstacles and minima if a global minimum does not exist. Finally, as we consider environment representation and algorithms used, we refer to (43). Exact methods of A*, Dijkstra's algorithms, and heuristic methods with genetic algorithm, tabu search, and ant colony optimization were compared and evaluated in context of GPP in grid environments with presentation of the benefits and shortcomings of both path planning approaches. Heuristic approaches performed not as effective compared to exact approaches. Nevertheless, exact approaches were found not appropriate for large grid maps. To address shortcomings of both approaches, a hybrid approach was devised.

3. RESEARCH SURVEY RESULTS

In the following section we present results of the conducted survey on different approaches to static maritime environment representation using ENCs for GPP. The papers were selected on inclusion criteria of global path planning (along with trajectory and route variants) in a static maritime environment with ENCs as a basis for the environment modelling. The survey results are presented chronologically with brief overviews of the methodology and short summaries in Table 1.

GPP and LPP for Unmanned Surface Vehicle (USV) has been considered in (44). The authors stated kinematic constraints of the turning circle which influence the reachability of the waypoints. Further, the created path should be smoothed and of continuous curvature. A two-step GPP algorithm was implemented on uniform discrete grids based on ENC data created using Bresenham's algorithm. In the first step the geometrical representation of the route was created. Then a reachability graph with consideration of the vessel's turning circle. For the continuous curvature, segments between waypoints were interpolated with Bezier curves. To create a trajectory, constant velocity was applied. The vessel size was reduced to one grid cell while the obstacles were enlarged with a tangentially added potential field at the border. An A* algorithm was used to determine the path to the destination. Since the vessel has constant velocity, kinematic constraints only allow straight line motion or turning manoeuvre with maximum curvature limited by the turning circle. Further, it is assumed that a change from linear to circular motion is possible immediately. To reduce number of waypoints Douglas-Peucker algorithm was used, and the continuity of curvature ensured by interpolation of Bezier curves. Finally, authors stated that regular grid size limits the approach for longer paths due to large size of the grid. They considered quadtree approach which enables adaptive cell size. The confidence of the chart data, objects and attributes were not considered.

Automatic route planning method based on trapezoidal mesh approach was taken in (45) where the route was considered along with hydrographic domain of the ship. It was considered for both static and dynamic situations. Mesh was created by the selection of the rectangular area and an object within. Vertices were then used for graph creation. For the path search Dijkstra's algorithm was used on the formed undirected graph. The method was tested on three test cases from which first two had a 10 m safety contour constraint, while the third had 20 m safety contour. This research was partially based on a safe ship trajectory and ENC data representation considered in (46). Instead of using regular grids, trapezoidal meshes were used to reduce the computation time. The data were first loaded from the ENC from which land areas, isobaths, and navigational dangers were selected. The objects were then integrated in all chart layers and a trapezoidal meshes created. To create a safe trajectory in ship encounter situation Dijkstra's algorithm was used. Although the authors stated that the method is applicable for predeparture and voyage phases, authors presented simulated ship encounter case only, so it is not included in Table 1.

ISO8211 open-source library for retrieving data from the ENC and establish a regular rectangular environment grid model was used in (47). The GPP approach considered an USV and improved A* with a pilot quantity guiding the heuristic function closer to the straight line between the start and target point. The weights were assigned according to navigability and adjacent cells. The distance multiplied by the pilot quantity was used as heuristic function thus ensuring the route optimality. Finally, improved A* algorithm was compared with Dijkstra's and A*. The improved A* algorithm had the shortest distance, least number of nodes and turns, however it traversed larger number of nodes compared to A*.

Year	**ENC features and vessel type**	**Environment creation and representation**	**Global path planning approach**	**Ref.**
2015	Single ENC, scale not stated. USV and other vessels.	Bresenham's algorithm. Regular grids with potential fields.	A* with Bezier curves for smoothing and Douglas-Peucker for waypoint reduction.	(44)
2017	ENC(s), scale not stated, isobaths. Ship.	Trapezoidal mesh created from rectangular area and single object within.	Dijkstra's algorithm.	(45)
2017	Single ENC, scale not stated. USV.	Regular grid.	Dijkstra, A*, Improved A* with guiding pilot quantity, smoothing with redundant node removal.	(47)
2018	ENCs, various scales, depth. Ship.	Triangulated Irregular Network. Free space and obstacle polygons.	Route binary tree.	(48)
2018	Adapted for ENC, general statement of object and features used. Autonomous ship.	ENC based potential field points, curves, and shapes. Navigational area represented as a total potential field.	Applicable for any path planning method.	(49)
2019	Single ENC, scale not stated. Ship.	Navigable and non-navigable area.	Multi-criteria route creation adapted with risk contours.	(50)
2019	Single ENC, scale not stated, depth points and contours. USV.	Regional square grid, feasible region and barrier.	Water depth risk level A* algorithm (WDRLA*).	(26)
2021	ENCs, various scales, depth. Ship.	Delaunay triangulation (DT) Irregular DT grid map.	L^+, Final Optimization L+ (FO L^+) with line-of-sight optimization.	(7)
2021	Single ENC, scale not stated. Ship.	Multilayer grid map.	Final-optimized A* (FO A*).	(51)
2021	Single ENC, scale not stated, depth. Ship.	Delaunay Chart Model based on DT, navigable and forbidden navigational area.	Tangent Based Method, Dijkstra's algorithm.	(52)

Table 1. Chronology of surveyed papers, ENC features used and vessel types, environment creation and representation with global path planning approaches.

Route binary tree based on ENCs was considered for generating a path in (48). Authors stated that typical path planning approaches such as A*, Dijkstra or Theta are optimal only for the route of constructed network created from the chart. They noted that route binary algorithms were limited to single chart only, therefore they considered use of multiple ENCs. A spatial navigation obstacle database and improved R-tree index algorithm was proposed and used. Shallow areas were determined, and the depth model created using a Triangulation Irregular Network (TIN) and ship's draft. As a solution for single chart usage, obstacles from available charts and were fused in a single spatial database. During the planning process, the search query of R-tree index was improved by using Minimum Bounding Rectangle (MBR).

Path-guided hybrid artificial potential field (PGHAPF) method for autonomous ships, applicable for offline and online planning, static obstacle, and collision avoidance was presented in (49). Authors did not use the ENCs explicitly, however the potential field method and environmental modelling was based on ENC chart objects (points, lines, and surfaces). The authors simulated automatic path planning for the own ship in the presence of irregular static obstacles by testing it with a U-shape obstacle trap situation and Goals Non-Reachable with Obstacles Nearby (GNRON) Problem.

Multi-criteria approach with risk contours to path planning by considering the criteria of safety, efficiency, convenience, and ability of navigation was considered in (50). The authors defined the risk as the probability of stranding, impact, capsizing and sinking, while they did not consider avoiding collisions with other ships. A circular unit assessment area of 6 minutes was set up, based on position fixing interval. The whole area was divided in navigable and non-navigable and navigational traffic risk with hazard indexes for depth, obstacles, and sea conditions with weights was defined. Furthermore, geometric analysis was carried out, determining the cohesion and the number of obstacles in the area and quantitatively joining them with risk values. According to these values, risk contours were created, i.e., lines of equal risk value that are the basis for the adaptation of paths. To obtain a solution they proposed an algorithm which inputs are departure and arrival points to define direction. Second algorithm created the entire route projection based on risk gradient and radius between two adjacent risk contours.

Water depth risk level A* algorithm (WDRLA*) based on ENC for surveying and mapping USV was proposed in (26). A uniform square grid with resolution of 25x25 m was selected with static obstacles and depth. The grid size was calculated based on USV size, turning radius, localization error, buffer zone and chart error. Water depth was extracted from depth points, contours, and isobath depth areas. Further, spline function method was used for interpolation from discrete water depth points. Based on the hydrodynamic analysis of the USV properties the minimum required water depth and depth hazard degree was derived. The heuristic function was then adjusted for the depth hazard. Similar approach, however for multi-objective Hybrid A* algorithm in a dynamic environment (MOHA*) was considered in (20).

Automatic route planning of ships and problems were considered in (7) and shortcomings and computation expense of grid approach over longer distances stated. The authors observed frequent usage of A*, Dijkstra's and Theta* algorithm based on grids and alternatives such as quadtrees and Delaunay triangulation (DT). Furthermore, they observed that in previous research actual water depths were not considered. The stated reason was computational cost, since it is difficult to estimate the depth of each cell based on vector data. Furthermore, depths on the ENCs are unevenly distributed, thus creating difficulties when creating a grid. In their approach, they created a map of depth points using Delaunay Triangulation (DT) and data from the ENC. Afterwards, L+ and FO L+ algorithms (Final Optimization L+) were applied in the limited area of the Mississippi River and the Gulf of Mexico. Authors did not consider the confidence of data, objects, and attributes of ENCs.

Final Optimized A* algorithm based on multilayer grids directly applicable in ECDIS was proposed in (51). The authors stated that although there are numerous articles regarding automatic path or route planning, only few are mature and applied on ECDIS platform. They employed quaternion ship domain, safety distance to static obstacles objects and 6 degrees of freedom (DOF) vessel model. Furthermore, they proposed a route tracking controller for route tracking.

An automatic route design algorithm based on novel environment modelling method was presented in (52). The process of route generation was divided in two stages of environment modelling and path planning. Two modes of design were created, Mode I (environment modelling with path generation) and Mode II (Mode I with optimization). The approach used was the Tangent Based Method, based on polygon obstacle model. It was presented and compared with Visibility Graph Method, Voronoi Diagram Method, and Maklink Graph Method. Contrary to Voronoi Diagram and Maklink Graph, the Tangent Based Method makes the path as close as possible to the obstacles. Thus, the shortest path is a common tangent between convex polygon boundary and convex polygon. Furthermore, they stated that path and route planning methods are well researched and developed. On the other hand, environment modelling is mostly based on abstract mathematical models which reflects in few practical approaches using charts. The proposed method was considered for a ship using the model including ship resistance, environmental disturbances, and forces of the hull. Several ship sizes were used, and experiments conducted in independently created software. After the model of the environment was created Tangent Graph Method was used for construction of the navigable network undirected graph, while the Dijkstra's algorithm was used to find the solution in the undirected graph. For the route design implementation and verification Dijkstra's algorithm with and without environmental factors was employed.

In this final paragraph of the section, we include papers which did not address in full our stated objective of research of static maritime representation, ENCs and GPP. However, they present interesting approaches or valuable observations. Although not explicitly dealing with GPP, in (53), authors considered the use of ENCs for dynamic mission planning as an improvement over static mission planning of autonomous surface vehicle (ASVs) used for bathymetric surveys. For this purpose, they used ENC_Reader within the Mission Oriented Operating System (MOOS) platform for mobile robots. ENC data in S-57 format were converted to ENC_DB database and grouped according to data geometry into points. Objects dangerous to navigation were defined by hazard levels, available by quantitative and qualitative data such as "Water Level Effect" attributes, when quantitative data is not available. According to the data, authors defined hazard levels from -1 to 5 and displayed them with different colors according to the danger. Furthermore, in (54) same authors considered the use of ENCs for GPP and autonomous navigation. They showed difficulties in ENC usage on an example for a chart at a scale of 1:10000 without a sufficiently detailed representation of the environment, notably by excessively increasing the scale larger than the compilation scale (overscale). The non-compliance of charts with the actual situation in the observed area was also noted, i.e., the limitations of generalization on the corresponding scale, which should also be indicated. Furthermore, there was a difference in the position of e.g., rocks, which due to the compilation process, can differ more than 40 m. As a solution to the problem of generalization on ENCs and inappropriate representation of the object size, they proposed to define objects in 2D instead of 1D, how it is currently defined for lines and or points which do not have scale. This would prevent the impact of generalization on the display of individual objects on the chart and the definition of the actual size when displaying on different scales. It was also stated that the display of the uncertainty of the data according to the above, defined by CATZOC, does not to accurately show uncertainty in the chart compilation process. They concluded that the charts, scales, and representation should be adapted to the size and maneuvering characteristics of ships sailing in the navigation area.

4. DISCUSSION

Our research objective was directed towards static maritime environment representation using ENCs in GPP. Starting from a broad perspective on separated subjects we focused on integrated approaches. In line with research objective, we can observe that ENC usage for static environment representation in GPP is not so extensive as we expected. Most of the researchers used single ENCs for their proposed GPP solutions and static environment modelling. The static environment is mostly represented as regular grids, triangulated irregular networks, followed by trapezoidal meshes and potential field. Furthermore, A* and Dijkstra's are the most common GPP algorithms used. Diverse types of vessels were considered including USVs, ships and autonomous ships. As a final observation, high-density bathymetric data and machine learning approaches were not implemented within narrowed context of GPP.

Limited usage of ENCs might be understandable since the IHO S-57 encoding standard was primarily designed for usage in ECDIS. There are applications which have simple to advanced possibilities to present ENCs, however they are primarily geospatial or navigational tools. Notably, geospatial tools have much greater extensibility with software libraries and programming capabilities. However, they are not designed for usage as background service for GPP or vessel modelling. On the other hand, navigational simulators are available, providing certified environment for various types of maritime training and experimenting. However, they are not free, are closed source with constrained experimentation possibilities outside of simulated environment. This is understandable due to simulator complexity and long-term investment in research and development from the manufacturers to comply with user requirements and legislative constraints. Coming from such perspective it is understandable that researchers devise simplified representations of simulated static environment and obstacles using programming language libraries or develop custom ENCs solutions, as it a common case.

Along custom ENC solutions, most of the researchers used single ENCs for their proposed GPP and environmental modelling. The complexities and generalization issues across different scales were observed and how they can negatively influence the path solution. The uncertainty and in-depth consideration of various ENC layers important for navigation were not extensively considered as well. Again, this is expected because adding objects and attributes other than the basic depth related or land objects increases computational cost and complexity. The implementation decision is weighted against perceived modest to marginal increase in path planning accuracy and complexity of implementation. This is increased even further when we consider more abstract elements such as recommended routes or mandatory traffic separation schemes which have not been included. Although these are not physical obstacles or bounds, nevertheless they should be accounted for. When comparing GPP and related elements of route creation in voyage planning, the navigator must consider confidence of data, and account for interpretation of available objects and attributes. However, the choice of complexity accounting for available ENC attributes and features in GPP and proper environmental model is not easy and will be further discussed.

Regular grids triangulated and irregular networks were the most common approaches for static maritime environment representation. As presented previously, regular grids have the main advantages in simplicity of generation and regularity. The disadvantage is the reduced accuracy of environment modelling and computational cost. Furthermore, the decision on resolution must be made depending on environment and obstacles. Vessel dimensions and manoeuvring properties must be considered as well, both in terms of cell size and connectivity. The vessel must traverse certain number of cells and connect to more distant cells to make a turn. To deal with large regular grid limitations quadtree implementation was suggested. The other preferred approach was the triangular irregular network. This polygon decomposition approach is very often based on the Delaunay triangulation (DT). It has the advantage that represents area and obstacles with smaller number vertices of irregular sized triangles. Moreover, it better reflects the variable depth or obstacle density present in the environment. Although a more accurate representation, it is a more complex model requiring topological data structure. Trapezoidal meshes with vertical decomposition were less commonly used, although they have advantage in linear relation of number of cells to number of polygon vertices and formation of adjacency graphs.

Furthermore, A* and Dijkstra's were the most common algorithms used for GPP in the conducted research. The known benefits of A* is the speed compared to Dijkstra's algorithm. This is due to heuristic function which directs graph traversal and reduces the number of visited nodes. However, A* heuristic function must not overestimate the path cost to the destination or in other words it must be admissible. Further, enough memory must be available to find the solution. The computational challenges are present for both Dijkstra and A* algorithms when used with large graphs and grids. To cope with this, node reduction techniques, alternatives to grids, adaptations of the original algorithms or other algorithms must be used. Finally, since the determined shortest or optimal path is usually not adequate for a turning and path following of the vessel, path processing methods must be used. Besides node reduction techniques such as Douglas-Peucker, some form of path smoothing is employed to create feasible vessel path. The Bezier curves, as one of the presented approaches which resolve path curvature constraints, are frequently used outside the presented limited ENC environment studied in our research.

The goal of the research was to investigate a narrower context than it is usually considered in both general and maritime path planning literature. We are aware that there is a trade-off between generality and detail for the presented subjects. However, broad, and narrow perspectives included and referenced literature should facilitate research for others interested in the presented interrelated problems. This includes both human perspective in current and future voyage planning and perspective of path planning for various levels of autonomy of different vessels. We presented challenges using S-57 ENCs both in terms of format constraints and static environment representation alongside improvements that S-100 products will bring. The properties of S-100 should be evaluated further, since we did not present in-depth analysis to avoid further broadening of the scope of the article. In line with that, the ENC limitations standards in terms of human legibility of charts should be compared side by side with machine-readability. As a closing observation, several interesting topics have been just touched upon. Standardised problems, benchmarks and even virtual test environments are available for computer science, robotics, and other interested communities. It would be beneficial if comparable complete solutions were available in the maritime domain for example based on ENC charts. Furthermore, game engines, physics simulators, geospatial platforms, contribution packages and libraries have already been considered and used in maritime context. Therefore, it is worth considering the next step, bridging the gap from classical navigational simulators and specialised specific domain research tools. Such integrated platforms would improve and facilitate interchange, quality, and reproducibility of the already coinciding research interests.

5 CONCLUSIONS

In the conducted research the aim was to investigate how is static maritime environment modelled using ENCs in GPP. Relevant publications on path planning in general and global path planning, electronic navigational charts and environment representation were evaluated. There is significant amount of literature presenting path planning and environment modelling in robotics, autonomous vehicle, and general maritime domains. It is similar with literature dealing with ENCs either from hydrographic, or navigational perspective.

However, usage of ENCs as basis for static environment modelling and GPP is not so common.

There are several reasons limiting extensive usage of current ENCs. The ENC format, original scope and relation to ECDIS, constrains the usage for other applications. Furthermore, with numerous objects and attributes the data adds complexity when used for GPP. The shortcomings of the IHO S-57 inflexibility are addressed in IHO S-100 products aligned with geospatial standards and data formats. However, it will take time to make the transition from S-57 to S-101 charts.

Most of the presented approaches used single ENCs for path planning. The static environment was mostly modelled in form of regular grids and triangulated irregular networks, followed by trapezoidal meshes and potential field approach. For GPP, A* algorithm and variants were used followed by Dijkstra's algorithm. To improve path search, A* was modified using water risk depth level, guiding pilot quantity and final optimization. Since the methods based on grids and networks usually produce paths with excessive number of nodes and turns not feasible for the vessel, using a form of node reduction and path smoothing has been used. This was carried out with redundant node removal, Douglas-Peucker algorithm and Bezier curve smoothing. Confidence and uncertainty of the charted data was not considered and basic ENC depth objects and attributes were used only. Chart error was included only in a single approach. The proposed approaches were considered for diverse types of vessels, including ships, autonomous and unmanned vessels.

For future research, detailed analysis of S-100 products will be conducted to assess possibilities for GPP and environment representation. Further, the testing and benchmarking environments available in other domains with platforms supporting usage of ENCs will be assessed as well.

REFERENCES

1. Šakan, D.; Žuškin, S.; Valčić, M.; Pavletić, D. Challenges of adaptive coastal voyage planning. In: *Proceedings of the 13th Annual Baška GNSS Conference* [Online]. 2019, p. 87–106. . [Accessed: June 2022]. Available at: <https://pfri.hr/web/hr/dokumenti/13-GNSS-2019_Final.pdf>.

2. Brčić, D.; Žuškin, S.; Valčić, S.; Rudan, I. ECDIS transitional period completion: analyses, observations and findings. *WMU Journal of Maritime Affairs* [online]. 2018, vol. 18, no. 2, p. 359–377. eISSN 1654-1642. [Accessed: June 2022]. Available at: < doi: 10.1007/s13437-019-00173-z>.

3. Sharma, A.; Kim, T.-E. Exploring technical and non-technical competencies of navigators for autonomous shipping. *Maritime Policy & Management* [online]. Apr. 2021. eISSN 1464-5254. [Accessed: June 2022]. Available at: < doi: 10.1080/03088839.2021.191487a>.

4. Luo, J.; Wan, X.; Duan, J. A new model of environment-aware geographic information services in e-navigation. *Journal of Navigation* [online]. 7 November 2019, vol. 73, no. 2, p. 471–484. eISSN 1469-7785. [Accessed: June 2022]. Available at: < doi: 10.1017/S0373463319000766>.

5. Maka, J.; Magaj, J. Data extraction from an electronic S-57 standard chart for navigational decision systems. *Zeszyty Naukowe/Akademia Morska w Szczecinie* [online]. 2012, vol. 30, no. 102, p. 83–8. [Accessed: June 2022]. Available at: <http://yadda.icm.edu.pl/baztech/element/bwmeta1.element.baztech-article-BWM7-0006-0013>.

6. Damerius, R.; Hahn, T.; Jeinsch T. Towards optimal motion planning of surface vehicles in confined waters. In: *IFAC-PapersOnLine* [online]. January. 2021, vol. 54, no. 16, p. 327–332. eISSN 2405-8963. [Accessed: June 2022]. Available at: < doi: 10.1016/J.IFACOL.2021.10.112>.

7. Liang, C.; Zhang, X.; Watanabe, Y.; Zhao, B. Novel L+ and FO L+ algorithms based on ENC data for automatic route planning of ships. *Ocean Engineering* [online]. September 2021, vol. 235, p. 109389. eISSN 0029-8018. [Accessed: June 2022]. Available at: <doi: 10.1016/j.oceaneng.2021.109389>.

8. Goerzen, C.; Kong, Z.; Mettler, B. A survey of motion planning algorithms from the perspective of autonomous UAV guidance. *Journal of Intelligent and Robotic Systems: Theory and Applications* [online]. November 2010, vol. 57, no. 65, p. 1–4. eISSN 1573-0409. [Accessed: June 2022]. Available at:< doi: 10.1007/s10846-009-9383-1>.

9. Châari, I.; Koubâa, A.; Trigui, S.; Bennaceur, H.; Ammar, A.; Al-Shalfan, K. SmartPATH: an efficient hybrid ACO-GA algorithm for solving the global path planning problem of mobile robots. *International Journal of Advanced Robotic Systems* [online]. January 2014, vol. 11, no. . eISSN 1729-8814. [Accessed: June 2022]. Available at: < doi: 10.5772/58543>.

10. Chen, Y.; Cai, Y.; Zheng, J.; Thalmann, D. Accurate and efficient approximation of clothoids using Bézier curves for path planning. *IEEE Transactions on Robotics* [online]. June 2017, vol. 33, no. 5, p. 1242–1247. eISSN 1552-3098. [Accessed: June 2022]. Available at: < doi: 10.1109/TRO.2017.2699670>.

11. Palikaris, A.; Mavraeidopoulos, A. K. Electronic navigational charts: international standards and map projections. *Journal of Marine Science and Engineering* [online]. April 2020, vol. 8, no. 4, p. 248, eISSN 2077-1312. [Accessed: June 2022]. Available at**: <** doi: 10.3390/JMSE8040248>.

12. Calder, B. R. On risk-based expression of hydrographic uncertainty. *Marine Geodesy* [online]. 2015, vol. 38, no. 2, p. 99–127. eISSN 1521-060X. [Accessed: June 2022]. Available at: <doi: 10.1080/01490419.2014.933141>.

13. Yan, J.; Guilbert, E.; Saux, E. An ontology for the generalisation of the bathymetry on nautical charts. *ISPRS Annals of the Photogrammetry, Remote Sensing and Spatial Information Sciences* [online]. 2014, vol. 2, no. 2, p. 1–7. eISSN 2194-9050. [Accessed: 2022]. Available at: <doi: 10.5194/isprsannals-II-2-1-2014>.

14. Contarinis, S.; Pallikaris, A.; B. Nakos. The value of marine spatial open data infrastructures—potentials of IHO S-100 standard to become the universal marine data model. *Journal of Marine Science and Engineering* [online]. July. 2020, vol. 8, no. 8, p. 564. eISSN 2077-1312. [Accessed: June 2022]. Available at: < doi: 10.3390/jmse8080564>.

15. Vagale, A.; Oucheikh, R.; Bye, R. T.; Osen, O. L.; Fossen, T. I. Path planning and collision avoidance for autonomous surface vehicles I: a review. *Journal of Marine Science and Technology* [online]. 2021, vol. 26, no. 4, p. 1292–1306. eISSN 1437-8213. [Accessed: June 2022]. Available at:< doi: 10.1007/s00773-020-00787-6>.

16. Vagale, A.; Oucheikh, R.; Bye, R. T.; Osen, O. L.; Fossen, T. I. Path planning and collision avoidance for autonomous surface vehicles II: a comparative study of algorithms, *Journal of Marine Science and Technology* [online]. 2021, vol. 26, no. 4, p. 1307–1323. eISSN 1437-8213. [Accessed: June 2022]. Available at: < doi: 10.1007/S00773-020-00790>.

17. Ferguson, D.; Likhachev, M.; A. Stentz. A guide to heuristic-based path planning. In: *Proceedings of the International Workshop on Planning under Uncertainty for Autonomous Systems, International Conference on Automated Planning and Scheduling [ICAPS]* [online]. 2005, p. 1–10. [Accessed: June 2022]. Available at:< http://cs.cmu.edu/afs/cs.cmu.edu/Web/People/maxim/files/hsplanguide_icaps05ws.pdf>.

18. Davoodi, M.; Panahi, F.; Mohades, A.; Hashemi, S. N. Multi-objective path planning in discrete space. *Applied Soft Computing* [online]. Jan. 2013, vol. 13, no. 1, p. 709–720. eISSN 1568-4946. [Accessed: June 2022]. Available at: <doi: 10.1016/j.asoc.2012.07.023>.

19. Raja, P. Optimal path planning of mobile robots: a review. *International Journal of the Physical Sciences* [online]. Feb. 2012, vol. 7, no. 9, p. 1314–1320. eISSN 1992-1950. [Accessed: June 2022]. Available at: < doi: 10.5897/ijps11.1745>.

20. Wu, M. Zhang, A.; Gao, M.; Zhang, J. Ship motion planning for MASS Based on a multi-objective optimization HA* algorithm in complex navigation conditions. *Journal of Marine Science and Engineering* [online]. Oct. 2021, vol. 9, no. 10, p. 1126. [Accessed; June 2022]. Available at: < doi: 10.3390/jmse9101126>.

21. Gonzalez, D.; Perez, J.; Milanes, V.; Nashashibi, F. A Review of motion planning techniques for automated vehicles. *IEEE Transactions on Intelligent Transportation Systems* [online]. vol. 17, no. 4, p. 1135–1145, Apr. 2016. [Accessed: June 2022]. Available at: <doi: 10.1109/TITS.2015.2498841>.

22. Latombe, Jean- Claude, 2012. *Robot motion planning.* 1991. Springer Science & Business Media, 2012. ISBN 9781461540229.

23. Souissi, O.; Benatitallah, R.; Duvivier, D.; Artiba, A.; Belanger, N.; Feyzeau, P. Path planning: A 2013 survey. In: *Proceedings of 2013 International Conference on Industrial Engineering and Systems Management* [online]. IESM, IEEE, Oct. 2013, p. 1-8.

24. Qureshi, A. H.; Miao, Y.; Simeonov, A.; Yip, M. C. Motion planning networks: bridging the gap between learning-based and classical motion planners. *IEEE Transactions on Robotics* [online]. vol. 37, no. 1, p. 48–66, Feb. 2021. [Accessed: June 2022]. Available at: <doi: 10.1109/TRO.2020.3006716>.

25. Tsardoulias, E. G.; Iliakopoulou, A.; Kargakos, A. Petrou, L.A Review of global path planning methods for occupancy grid maps regardless of obstacle density. *Journal of Intelligent and Robotic Systems: Theory and Applications* [online]. vol. 84, no. 1–4, pp. 829–858, May 2016. [Accessed: June 2022]. Available at: <doi: 10.1007/s10846-016-0362-z>.

26. Liu, S.; Wang, C.; Zhang, A. A method of path planning on safe depth for unmanned surface vehicles based on hydrodynamic analysis. *Applied Sciences* [online]. vol. 9, no. 16, p. 3228, Aug. 2019. [Accessed: June 2022]. Available at: <doi: 10.3390/app9163228>.

27. Votion, J.; Cao, Y. Diversity-based cooperative multivehicle path planning for risk management in costmap environments. *IEEE Transactions on Industrial Electronics* [online]. vol. 66, no. 8, pp. 6117–6127, Aug. 2019. [Accessed: June 2022]. Available at: < doi: 10.1109/TIE.2018.2874587>.

28. Nie, P.; Chen, Z.; Xia, N.; Huang, Q.; Li, F. Trajectory similarity analysis with the weight of direction and K-neighborhood for AIS data. *ISPRS International Journal of Geo-Information* [online]. vol. 10, no. 11, p. 757, Nov. 2021. [Accessed: June 2022]. Available at: <doi: 10.3390/ijgi10110757>.

29. Alexander, L.; Brown, M.; Greenslade, B.; Pharaoh, A. Development of IHO S-100: The new IHO geospatial standard for hydrographic data. *International Hydrographic Review* [online]. vol. 8, no. 1, p. 56–62, 2007, [Accessed: Mar. 09, 2022]. Available at: < .https://scholars.unh.edu/cgi/viewcontent.cgi?article=2033&context=ccom>.

30. Kristić, M.; Žuškin, S.; Brčić, D.; Valčić, S. Zone of confidence impact on cross track limit determination in ECDIS passage planning. *Journal of Marine Science and Engineering* [online]. 2020, Vol. 8, Page 566, vol. 8, no. 8, p. 566, Jul. 2020. [Accessed: June 2022]. Available at: < doi: 10.3390/JMSE8080566>

31. NOAA ENC Direct to GIS - CKAN [Dataset]. < https://archive.ph/oQH4r>. [accessed Mar. 11, 2022].

32. Warmerdam, F. The geospatial data abstraction library. In: *Open Source Approaches in Spatial Data Handling* [online]. Berlin, Heidelberg: Springer Berlin Heidelberg, 2008, p. 87–104. [Accessed: June 2022]. Available at: <doi: 10.1007/978-3-540-74831-1_5>.

33. Junho, M.; Jiyoon, K. Research on voyage navigation S/W development architecture using open source base GIS modules. In: *Free and Open Source Software for Geospatial (FOSS4G) Conference Proceedings* [online]. vol. 15, p. 23, 2015, [Accessed: June 2022]. . Available at: <https://doi.org/10.7275/R5736P3N>.

34. Hare, R.; Eakins, B.; Amante, C. Modelling bathymetric uncertainty. *The International Hydrographic Review* [online]. Jun. 2011, [Accessed: Jan. 04, 2022]. Available at: <https://journals.lib.unb.ca/index.php/ihr/article/view/20888>.

35. Skopeliti, A.; Stamou, L.; Tsoulos, L.; Pe'eri, S. Generalization of soundings across scales: from DTM to harbour and approach nautical charts, *ISPRS International Journal of Geo-Information* [online]. vol. 9, no. 11, p. 693, Nov. 2020. [Accessed: June 2022]. Available at: < doi: 10.3390/ijgi9110693>.

36. Blindheim, S.; Johansen, T. A. Electronic navigational charts for visualization, simulation, and autonomous ship control. *IEEE Access* [online]. p. 1–1, 2021. [Accessed: June 2022]. Available at: <https://ieeexplore.ieee.org/document/9666898>.

37. Duan, J.; Wan, X.; Luo, J. A review of universal hydrographic data model. *Survey Review* [online]. vol. 53, no. 377, p. 183–191, 2021. [Accessed: June 2022]. Available at: < doi: 10.1080/00396265.2019.1708048>.

38. Powell, J. The new electronic chart product specification S-101: an overview. *TransNav, the International Journal on Marine Navigation and Safety of Sea Transportation* [online]. vol. 5, no. 2, p. 167–171, 2011. [Accessed: June 2022]. Available at: <https://www.transnav.eu/Article_The_New_Electronic_Chart_Product_Powell,18,281.html>.

39. Sanchez, A.; Bosselmann-Borsos, V.; Di Lieto, A. A practical approach to the production of ENC with high density bathymetric content. *The International Hydrographic Review* [online]. 2019, [Accessed: Jan. 02, 2022]. Available at : <https://journals.lib.unb.ca/index.php/ihr/article/view/31479>.

40. Lee, W.; Choi, G. H.; Kim, T. W. Visibility graph-based path-planning algorithm with quadtree representation. *Applied Ocean Research* [online]. vol. 117, p. 102887, Dec. 2021. [Accessed: June 2022]. Available at: < doi: 10.1016/j.apor.2021.102887>.

41. Wise, K. D.; Bowyer, A. A survey of global configuration-space mapping techniques for a single robot in a static environment. *The International Journal of Robotics Research* [online]. vol. 19, no. 8, p.762-779, 2000. [Accessed: June 2022]. Available at: <https://doi.org/10.1177/02783640022067157>.

42. Debnath, S. K.; Omar, R.; Latip, N. B. A. Comparison of different configuration space representations for path planning under combinatorial method. *Indonesian Journal of Electrical Engineering and Computer Science* [online]. vol. 14, no. 1, p. 1–8, 2019. [Accessed: June 2022]. Available at: <http://doi.org/10.11591/ijeecs.v14.i1.pp1-8>.

43. Chaari, I.; Koubaa, A.; Bennaceur, H.; Ammar, A.; Alajlan, M.; Youssef, H. Design and performance analysis of global path planning techniques for autonomous mobile robots in grid environments. *International Journal of Advanced Robotic Systems* [online]. vol. 14, no. 2, 2017. [Accessed: June 2022]. Available at: <doi: 10.1177/1729881416663663>.

44. Blaich, M.; Wirtensohn, S.; Reuter, J.; Hahn, A. Trajectory generation for vessels using a reachability graph. In: *OCEANS 2015-Genova* [online]. Sep. 2015. [Accessed: June 2022]. Available at: <doi: 10.1109/OCEANS-Genova.2015.7271471>.

45. Wielgosz, M.; Mąka, M. Route optimization in the restricted area taking into account ship safety zones. In: *Marine Navigation - Proceedings of the International Conference on Marine Navigation and Safety of Sea Transportation* [online]. TRANSNAV 2017, 2017, p. 57–63. [Accessed: June 2022]. Available at: <https://www.taylorfrancis.com/chapters/edit/10.1201/9781315099132-5/route-optimization-restricted-area-taking-account-ship-safety-zones-wielgosz-m%C4%85ka?context=ubx&refId=30e3d69c-1be5-4bdd-87ae-22abdd26b92a>.

46. Pietrzykowski, Z.; Magaj, J.; Mąka, M. Safe ship trajectory determination in the ENC environment. In: *Int. Conf. on Transport Systems Telematics* [online]. TST 2014. Oct. 2014, vol. 471, p. 304–312. [Accessed: June 2022]. Available at: <doi: 10.1007/978-3-662-45317-9_32>.

47. Wang, Y.; Liang, X.; Li, B.; Yu, X. Research and implementation of global path planning for unmanned surface vehicle based on electronic chart. In: *Int. Conf. on Mechatronics and Intelligent Robotics*

[online]. 2017, vol. 690, p. 534–539. [Accessed: June 2022]. Available at: < doi: 10.1007/978-3-319-65978-7_80>.

48. Jia, S.; Dai, Z.; Zhang, L. Automatic ship routing with high reliability and efficiency between two arbitrary points at sea. *Journal of Navigation* [online]. vol. 72, no. 2, p. 430–446, Mar. 2019. [Accessed: June 2022]. Available at: < doi: 10.1017/S0373463318000814>.

49. Lyu, H.; Yin, Y. Fast path planning for autonomous ships in restricted waters. *Applied Sciences* [online]. vol. 8, no. 12, p. 2592, Dec. 2018. [Accessed: June 2022]. Available at: <doi: 10.3390/app8122592>.

50. Jeong, M.-G.; Lee, E.-B.; Lee, M. Jung, J.-Y. Multi-criteria route planning with risk contour map for smart navigation. *Ocean Engineering* [online]. vol. 172, p. 72–85, Jan. 2019. [Accessed: June 2022]. Available at: < doi: 10.1016/j.oceaneng.2018.11.050>.

51. Wang, Q.; Zhong, M.; Shi, G.; Zhao, J.; Bai, C. Route planning and tracking for ships based on the ECDIS platform. *IEEE Access* [online]. vol. 9, p. 71754–71762, 2021. [Accessed: June 2022]. Available at: <doi: 10.1109/ACCESS.2021.3078899>.

52. Pan, W.; Xie, X.L; He, P.; Bao, T.T.; Li, M. An automatic route design algorithm for intelligent ships based on a novel environment modelling method. *Ocean Engineering* [online]. vol. 237, p. 109603, Oct. 2021. [Accessed: June 2022]. Available at: < doi: 10.1016/J.OCEANENG.2021.109603>.

53. Reed, S.; Schmidt, V. E. Providing nautical chart awareness to autonomous surface vessel operations, In: *OCEANS 2016 MTS/IEEE Monterey, IEEE* [online]. Sep 28, 2016, p. 1–8. [Accessed: June 2022]. Available at: <doi: 10.1109/OCEANS.2016.7761472>.

54. Schmidt, V.E.; Reed, S. Autonomous navigation on (US) nautical charts, In: *2018 Canadian Hydrographic Conference* [online]. 2018, p. 10. [Accessed: June 2022]. Available at: <https://ccom.unh.edu/sites/default/files/publications/ENCsforASVs_VS_vfinal.pdf>.