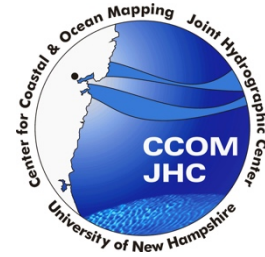# Autonomous Navigation on (US) Nautical Charts

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Abstract

Although much interest has been given to the use of autonomous surface vehicles (ASVs) for hydrographic data collection, little thought has been given to the utility of currently available chart products for safe navigation of the ASV itself. In the United States, chart products are currently available in digital form, as both cartographic raster images of traditional paper charts and as vector representations of cartographic data, ("BSB" files and electronic nautical charts (ENCs), respectively). Here we evaluate these chart products with an eye to common methods by which artificial intelligence (AI) algorithms would likely use them. We find that the raster cartographic nature of BSB nautical charts leaves a complex interpretation problem for computers to recognize and understand their nuance. However, the BSB cartographic representation holds useful information that can be equally difficult to infer from electrical nautical charts, particularly when size of objects are implicitly tied to the scale of the chart. Further we find that while ENCs provide near instantaneous interpretation, the data must be reorganized for fast search. Additionally, some features, notably docks and breakwaters, are represented in the ENC in a single dimension (a line) even though they subtend a finite second dimension, forcing the AI algorithm to buffer objects to ensure safe navigation. When objects fail to have explicit measurements (for example a measured depth) encoded in the ENC, one is left to interpret their relative hazard from qualitative descriptions. This interpretation can be particularly challenging when the qualitative descriptions are referenced to the local vertical datum. Finally, the ENC's compilation scale, when encoded, is particularly useful as it provides an implicit measure of uncertainty about the chart information, determining the granularity with which navigation choices can be made.

Introduction

Although much thought has been given to the use of autonomous systems for the collection of hydrographic data for the creation of nautical charts, little thought has been given to suitably of nautical charts for use by autonomous systems in their own navigation. In this paper we discuss likely methods that autonomous systems will use nautical charts, pitfalls that developers are likely to make in proper chart interpretation and suggest ways in which hydrographers and cartographers might improve charting methods and chart formats to better accommodate them.

# Use of Nautical Charts by Autonomous Surface Vessels.

Navigation and path finding by robotic systems can be broadly broken down into two types – deliberative path planning in which the system considers a fixed map and finds the optimal path between start and end positions, and reactive object avoidance in which a vessel quickly evaluates its location relative to known close-aboard obstacles and ensures choices of heading and thrust will avoid them.

While there are many methods for path planning, A* (A-star) is a classic that remains widely used throughout robotics. A* normally operates on a rectilinear grid. Beginning at the starting grid cell, A* considers the cost of a potential move to adjacent cells. Cost may constitute distance traveled, the energy expended, the time required, the risk of running aground or some combination of these. Cells are explored prioritizing those with the lowest cost along with a search preference in the direction of the goal cell. A* finds the optimal path without the need to exhaustively explore the entire search space. (Figure 1) It is this underlying grid that one seeks to create upon which a robotic vessel can execute a planner such as A*.

Figure 1. An illustration of classic path planning algorithms in robotics. A* (A-star) remains widely used and provides the optimal path without requiring a global search of the space.

However, a navigator may find himself off his planned path, due to wind, currents, or other interfering vessels and having to maneuver quickly to avoid near-by obstacles. Figure 2 illustrates the case, in which a planned path has been artificially placed over several shoal areas marked as polygons. In this example, heading choices toward a hazard that falls within the safety zone (red box) are penalized and the penalty is increased as the hazard approaches. The task here is to devise a methodology that allows the navigator to quickly identify close-aboard hazards from the chart so that his actions do not put his vessel in harm's way.
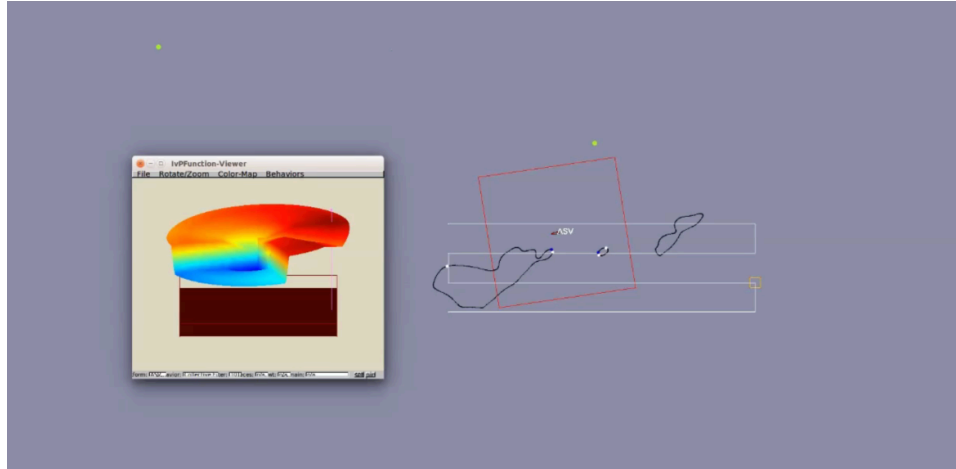
Figure 2. Here reactive object avoidance is illustrated in which a planned path has been deliberately placed atop hazards to navigation (black polygons). The algorithm penalizes headings in the direction hazards (indicated by blue in the inset objective function plot).

Challenges to Chart-based Navigation

Deliberative Path Planning

Here we consider methods by which grids might be generated from electronic nautical charts for robotic planning algorithms such as a A*. For illustration, the left image in Figure 4 shows a portion of the Portsmouth Harbor electronic nautical chart (US5NH02) viewed at chart scale (inset displayed at 10,000x1). This is the highest resolution chart available for this area. Unfortunately, at this scale the chart is not suitable for navigation in the vicinity of the coastline. When approaching the pier one desires to view the chart at a "navigation scale" as shown in the image on the right. However, here the chart is viewed "over-scaled". Neither the data, nor the knowledge of the seafloor, shoreline, piers or hazards are depicted at a single scale in this image. The resulting representation is highly misleading for human and robotic mariners alike and can be unsafe.
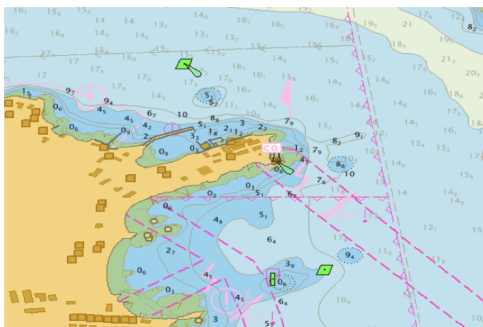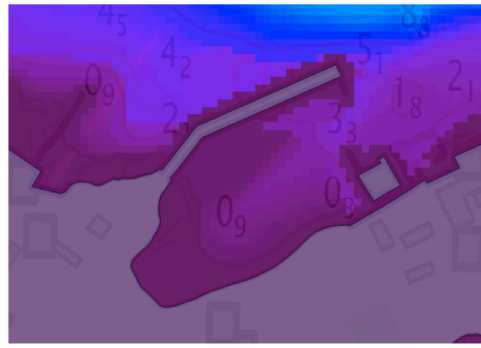

Caris Base Editor, Viewed at Chart Scale
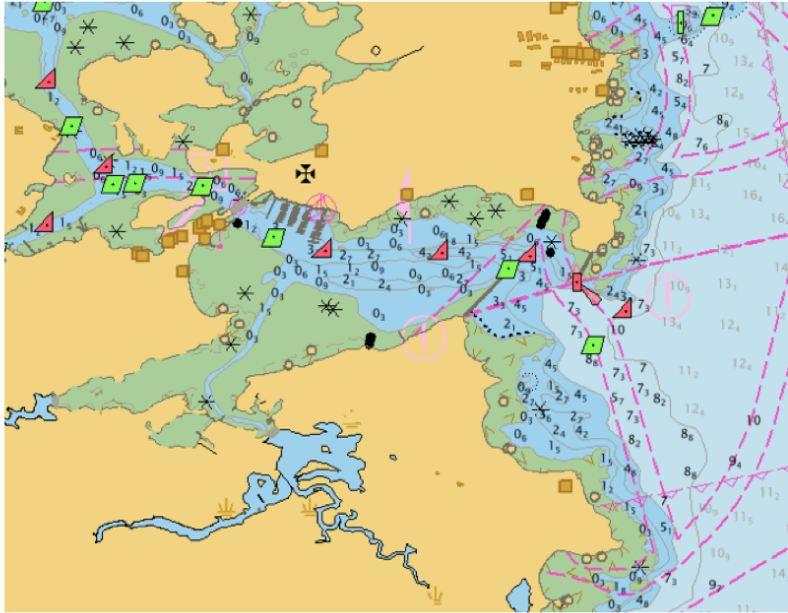

"Navigation" Scale

Caris Base Editor, Viewed at Scale   0.5 mm grid plus 0.5 mm buffering

Figure 4. In the upper the left, a portion of the Portsmouth Harbor chart is shown at scale. However, the chart resolution at this scale is generally inadequate to safely approach the coast. One desires a view closer to the "Navigation scale" representation shown in the upper right. In this over-scaled view, features are not uniformly represented at a single scale. The lower right image properly represents the chart at scale for this area. Thus, we generate a grid for robotic path planning (lower right) that ignores the vector representation of the data to retain the proper resolution of features. (Color indicates depth, or risk of grounding)

Clearly the problem lies in attempting to use the chart in a way in which it was not intended. The intended scale of a raster chart was always clear, as its very nature prevented a misleading representation. The intended scale of a vector electronic chart is less so, as vector graphics are, by definition, scale independent. In fact, the concept of chart scale on some vector objects makes little sense. A point simply has no scale and a line has scale only in a single dimension. Thus, while annotation of "chart scale" in the metadata is helpful (and we use it), one is too easily tempted to use the power of vector graphics, over-zooming displays or equivalently, producing an A* grid with an artificially high resolution. Figure 4 also depicts the chart at scale, zoomed in to a practical navigation level and shows our representation of the data where color indicates relative risk in an attempt to properly represent its underlying fidelity for robotic navigation.

"Little Harbor" Represented at Chart Scale

**Figure 5. "Little Harbor" and it's associated marina shown here at chart scale (20000:1). Safe navigation into the harbor is at best difficult at this scale, and yet it is the highest scale NOAA chart of the area.**

As another example, consider Figure 5, in which a harbor and marina are shown at chart scale for the single chart covering the area. Here again the scale of the chart is inadequate for navigation. Thus, we zoom the chart in to more clearly find a path (Figure 6, left image), but find that the rocks, whose symbol, when viewed at scale covered some 40 m in diameter, now only covers 10. While the location of the rock in the ENC is represented as a point with great precision, the actual location of the rock, because of the chart compilation process, may be anywhere within that 40 m circle, or in some cases outside it. Thus, to safely navigate on the chart we buffer the rocks at their compilation scale size as shown in Figure 6 (right image).
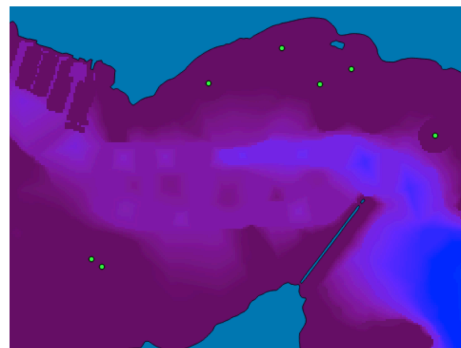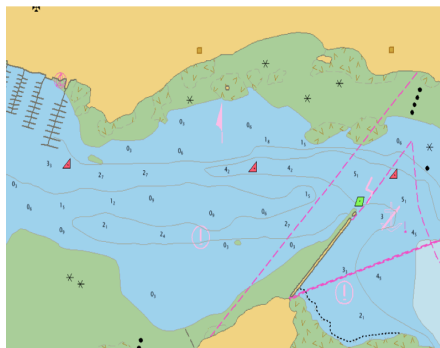
"Little Harbor" Represented at "Navigation" Scale

Figure 6. Little Harbor (left), shown at a level conducive to navigation. However, chart features are no longer represented uniformly at scale. Our representation (right) buffers objects to their original representation at chart scale.
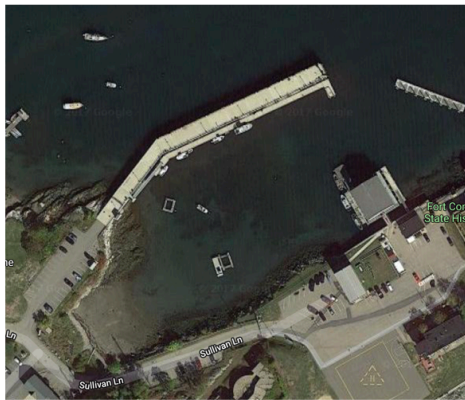
Google Maps

0.5 mm grid plus 0.5 mm buffering

Figure 7. Satellite image and ENC images of the University of New Hampshire Pier Facility. A floating pier exists adjacent to the fixed pier but is not represented in the ENC where only the spatial extent of the fixed pier is shown. Similarly, the breakwater, (installed in 2006) has been omitted.

Another challenging aspect in the use of nautical charts for navigation of autonomous vessels is simply their completeness. Figure 7 illustrates two examples by comparing a satellite image (left) with the corresponding ENC (right). Here a floating pier exists adjacent to the fixed pier but is not wholly represented in the ENC. NOAA's Nautical Charting Manual provides guidance for the representation of multiple piers as a single unit when the compilation scale prevents their clear depiction.[REF] Unfortunately, there is no guidance specifying that the resulting depiction should encompass the union of the represented structures. Maps generated from ENCs for safe autonomous navigation must then buffer around such objects guessing what might actually exist, but was not depicted in the cartographic representation.

Figure 7 also shows a floating breakwater in the upper right of the satellite image. This breakwater was installed in 2006 but remains unrepresented in the chart. The omission likely results from a gap in coverage between folks who delineate coastline and those who map coastal hazards. [A chart discrepancy has been filed with NOAA for this breakwater.]

Finally, we present a long-known issue with cartographic representations that is all the more challenging for robotic systems. Figure 8 depicts a raster chart where the word "Breakers" indicates white water that mariners should avoid. The satellite image overlain on the chart shows that the actual breakers are some distance, about 88 m from the represented location. The right image shows the ENC overlain on a bathymetric grid. No shoal area exists where the breakers are indicated. The bathymetry further suggests that the white water in the satellite image is the correct location. There was simply insufficient space on the raster chart to write "Breakers" where the breakers actually exist. The green and red dots in the two images indicate the reported position of "water turbulence" in the associated electronic nautical chart, precisely where the "Breakers" had been on the raster predecessor. However, without the

display limitation of the raster representation the reported location of the hazard simply looks misplaced in the ENC.

| Raster Chart and Satellite Image | ENC with Bathymetric Survey Data |
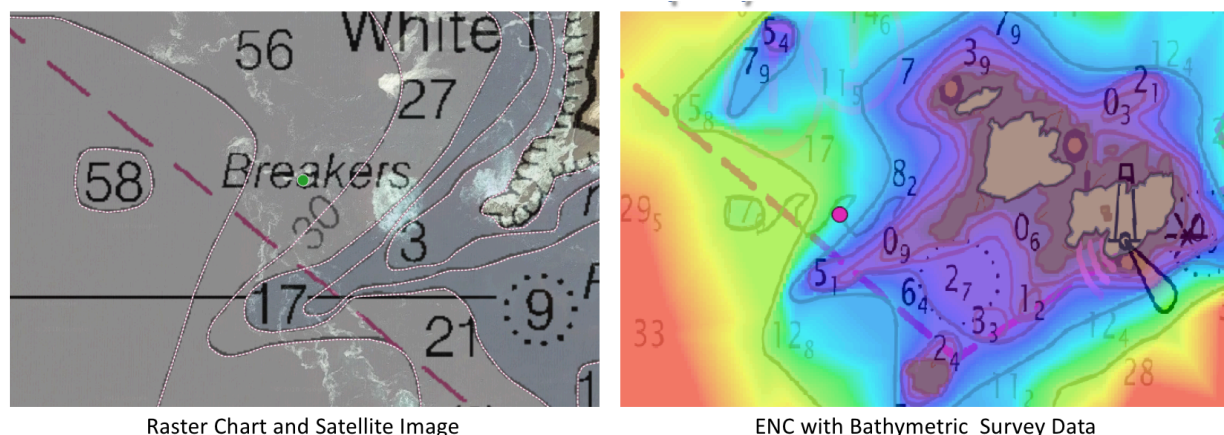
Figure 8. The raster chart with satellite image overlay (right) shows the word "Breakers" indicating hazardous water conditions. However, the location of the actual hazard is some 88 m distant from the actual hazard, which is apparent as white water in the satellite image, and confirmed by the underlying bathymetry in the right image. The location is misrepresented due to the cartographic depiction.

The kind of cartographic nuance illustrated by the "Breakers" example is very difficult for robotic vessels to understand from what is provided in the electronic nautical chart. The utility of a coastal chart is all but lost if one must buffer all objects conservatively to allow for where they might have been placed in a raster representation. Satellite imagery or other sources of data would be required to confirm the proper location.

Rather, one desires a new position encoding scheme for objects in the chart - one encoding that reports the actual position of the hazard as well as it can be measured, and a second providing an offset from that position for recommended display location. In this way, the accuracy of the data can be maintained, the precision with which it is reported can accurately reflect this accuracy and yet guidance can be provided to safely move the object's representation for clearity on a display for human mariners.

Reactive Obstacle Avoidance

Despite a safely planned path, a navigator may find himself off his planned path, due to wind, currents, or other interfering vessels and having to maneuver quickly to avoid near-by obstacles. Hazards to navigation are generally represented as points or polygons in electronic nautical charts, and algorithms such as the one described in the introduction can be created to avoid them. One need only the ability to quickly identify these hazards in real-time.

When a human mariner looks at a chart for hazards he identifies his own location on the chart and scans the immediate area. Unfortunately, the S-57 standard for electronic nautical charts is

indexed by feature type and then ancillary attributes of these features give their location. Thus, to identify local hazards to navigation one must read the entire chart, querying every object's location. This proves impractical and artificial systems must reorganize the chart material for live applications.

ECDIS systems suffer from this same problem. Their relatively incapable display systems cannot use electronic charts directly. They instead produce proprietary *System* ENCS (SENCS), which are small spatial tiles of the chart that may be quickly read from memory and displayed.

"C-Squares" Indexing	"R-Tree" Indexing

Proposal to Include a Grid Referencing System in S-100, *HSSC, Singapore, October 2009*

Y. Yu, H. Zhu, L. Yang, and C. Wang, "Spatial Indexing for Effective Visualization of Vector-Based Electronic Nautical Chart," *(ICIICII)*, 2016, pp. 323–326.

Figure 3. "C-Squares" indexing is a spatial indexing method and ASCII nomenclature that has been proposed for the IHO S-100 standard. Alternatively, spatial databases used in GIS applications often utilize a variant of "R-Tree" indexing, which also provides a hierarchical index for fast spatial search. Either method is a viable option for on-disk spatial indexing and storage of nautical chart information.

Indeed, this kind of "spatial indexing" is not new and other solutions exist. A proposal to S-100 suggests the use of "c-squares" indexing, which provides an ASCII nomenclature and method for hierarchically tiling the globe.[REF] Similarly, modern spatial databases use methods such as "R-Tree" indexing, which spatially index the data using dynamic methods that are optimized for the data's spatial distribution.[REF] These methods are appealing because the data itself can be represented on disk in a hierarchical format along with these indices, allowing fast retrieval of objects in the immediate vicinity of a vessel without reading the entire file.

Discussion:

These examples illustrate that proper interpretation of an electronic nautical chart is confused by the fact that the vector representation of data must be convolved with the chart compilation scale for a proper understanding. But because points and lines cannot, by definition, be represented at any scale, one must further understand the cartographic limitations of their representation on raster versions of the chart to interpret the hazard properly. These

cartographic limitations will depend on the varying practices from hydrographic office to hydrographic office and as such leaves too much that must be implicitly inferred by the autonomous mariner and could become unsafe.

An intermediate solution to this problem is to forbid the representation of any object within a nautical chart by points or 1D lines. By requiring all objects to have a complete 2D representation, as a minimum non-collinear three-vertex polygon, the uncertainty in the cartographic generalization process that results from compiling data to a fixed scale can be explicitly encoded. A 1 m sized rock, whose intended display on a nautical chart viewer is a 2 mm asterisk (*) would be represented in a harbor chart compiled at 20000:1 not as a 0 m diameter point, but as a 40 m diameter circular polygon. When viewed at chart scale, the rock would display at the 2 mm. When viewed at higher scales the rock would be displayed as a larger polygon thus accurately reflecting the cartographic license applied during compilation.

For those familiar with the production of raster charts and their subsequent conversion to electronic form in vector format, the limitations of compilation scale are clear. But for those without this history who may be writing algorithms to safely navigate vessels using electronic charts, the vector-based and thus scale-independent format of these charts, can be misleading. In science education we teach that one should not report a measurement with more precision than the measurement's uncertainty. However, in electronic nautical charts objects are located with near arbitrary precision and their measurement uncertainty is encoded elsewhere, perhaps in the Categorical Zone of Confidence or CATZOC attribute, or indirectly through compilation scale. Note however that CATZOC, which is meant to characterize the combined uncertainty of the underlying data and its cartographic representation is applied without regard to the compilation scale of the underlying chart and thus may not accurately represent the uncertainty in the generalization process. Further, even knowledge of the compilation scale provides little guidance on the likely actual location of hazards such as the "Breakers" example provided, whose location has been moved for cartographic depiction. These must be re-encoded with accurate positions and optional recommended display offsets.

Many of the issues raised here ultimately result from attempting to navigate near coastlines on electronic nautical charts at a scale that was not intended. Much of the coastal representation on the chart exists to allow mariners without global positioning systems to discern their position relative to prominent landmarks. The depiction is not, actually intended to provide a compete hazard avoidance map, or even to accurately represent piers and other structures such that a mariner might navigate close to shore on the chart alone. To be sure, it has been impractical for hydrographic agencies to produce charts with sufficient resolution and accuracy that robotic vessels might navigate without external sensors. But this is changing.

For a chart that depicts coastline to be "fit for purpose" it must represent hazards at a scale commensurate with the size and maneuverability of the vessels expected to navigate those waters and the type of navigation they are likely to do. For example, if no chart containing coastline were compiled at less than 5000:1 the representation of objects at chart scale would more closely approximate the underlying measurement capability and provide features

commensurate with the size and maneuverability of most ocean-going vessels navigating there. Higher scale charts might be more appropriate in berthing areas regardless of vessel maneuverability to facilitate approach to a pier and docking. Electronic charts might be encoded not at a fixed compilation scale, but spatially indexed and encoded at a variable compilation scale to ensure the representation remains fit for navigation.

Acknowledgements

References:

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 "Spatial Indexing for Effective Visualization of Vector-Based Electronic Nautical Chart," Y. Yu, H. Zhu, L. Yang, and C. Wang, *(ICIICII)*, 2016, pp. 323–326.

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