Nautical Chart Awareness for Autonomous Surface Vehicles

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Abstract

There is great potential for the use of Autonomous Surface Vehicles (ASVs) in seafloor mapping, given their ability to increase survey efficiency. In order to efficiently function in an unstructured environment, robots must be able to use their sensory information to make short and long term decisions. To accomplish important tasks such as avoiding obstacles, advanced path planning, and determining what obstacles from the Electronic Nautical Charts (ENCs) are in the field of view of the sensor, it is advantageous for the ASV to be able to read and understand the information from ENCs and make decisions as a human mariner would. The data from the ENCs will be used to populate a special database, which will be made available to a system that monitors the current and planned trajectory. This system uses the ENC database and the current and planned trajectory to give guidance to the helm to help make chart-informed navigation decisions. Furthermore, the ENC's data will also help the ASV place its measurements into a reference base which allows the ASV to achieve a higher level of autonomy.

Introduction

For Autonomous Surface Vehicles (ASVs) to become practical tools for hydrography, they require a high level of autonomy. However, many ASVs typically have limited autonomy because they use static mission planning with marginal environmental awareness. ASVs, having no *a priori* knowledge of the world around them, must wholly rely on operators to avoid obstacles, shoals and shorelines during mission planning. With static mission planning, operators must assume that the environment is fully known and consequently the optimal path, once determined, stays constant throughout the mission. As a result, mission planning then becomes labor intensive and does not scale to management of multiple vehicles. Therefore, an ASV that is provided *a priori* knowledge of its environment operates with great advantage.

ASVs that utilize dynamic mission planning have the potential to react to changes in the environment and update their optimal path. However, to use dynamic mission planning, ASVs must be able to sense obstacles themselves in real time. Like human mariners, ASVs observe the environment around them using visual observations, radar and sonar measurements. However, reliable and robust sensor operation is challenging in a marine environment. Sea state, wind, fog, sea spray, sun glint from the sea surface, and bubbles in the water column all lead to an extremely harsh environment that challenges sensor operation. Human mariners suffer from these conditions too and augment their understanding of their environment with additional data, often in the form of nautical charts. Nautical charts give mariners *a priori* knowledge of their operating environment, providing indications of rocks and other obstructions, navigational aids, water depths and shore lines. Nautical charts can provide guidance when the path is unclear and context to sensor measurements that are subject to uncertainty. Therefore, ASVs utilizing dynamic mission planning can also operate to great advantage if, like their human counterparts, they can learn to read a nautical chart.

The goal of this research is to use the information in Electronic Nautical Charts (ENCs) to allow an ASV to make decisions with knowledge of the surrounding environment, as a human mariner would. For example, a mariner whose path crosses a charted underwater rock or wreck would avoid the obstacle at a safe distance while still maintaining a close proximity to the desired path. An ASV should do the same.

In addition to providing knowledge of hazards during navigation, knowledge of nautical charts can provide context to measurements made by ASVs. For example, an ASV can determine what obstacles from the ENC should be in the field of view of a sensor. Knowing which obstacles are in a sensors field of view would allow the ASV to adjust the confidence in its measurements accordingly.

Our hypothesis is that implementing nautical chart awareness will increase the ASV's autonomy and decrease the amount of operator-ASV interaction. It will accomplish this by providing a more holistic understanding of the vehicle's environment allowing for optimal obstacle avoidance decisions, reactive, behavior-based mission plans, and increased sensor reliability.

Previous Work

There has been extensive work on the field of autonomous marine robotics and especially in the subject of obstacle avoidance (OA). Larson [1], [2] used a two pronged approach to OA by dividing it into the "far-field" and "near-field." In the far-field, Larson determined stationary obstacles from ENCs and moving obstacles from AIS and Automated Radar Plotting Aid contacts. They then used that information to avoid obstacles but stayed on original path as much as possible. In the near-field, they used a behavior-based model where decisions are made based on votes from the OA sensors and the path planner. As a result, this near-field model avoids nearby obstacles independently of the mission. This OA behavior based model is similar to the approach discussed in this paper.

Almeida [3] used radar information and remote vision for the primary sensors for OA. Based off of the trajectory of the objects, the object was given a threat level to help to decide upon potential avoidance procedures. This concept of using a threat level to determine risks of collision for different types of obstacles is a novel concept and will be used in this approach.

Elkins [4] implemented an autonomous system that included a World Map Server (WMS), which provided information on the maritime environment to the ASV. The WMS was populated with data from Digital Nautical Charts, a precursor to ENCs, and the fused data from their sensors to determine what each sensor should see. However, at the time the article was written, obstacle avoidance and path planning using WMS had not been implemented.

The approach described below will similarly provide nautical chart information for obstacle avoidance, path planning and sensor robustness.

Proposed Implementation

Due to the wide variety of vehicle navigation and control systems, separating the higher level vehicle autonomy from the lower level controls using a backseat driver is necessary to allow for nautical chart awareness to be rapidly implemented on many different ASVs. In this organization, the backseat driver runs the higher level autonomous systems, which determine the desired speed and heading. The lower lever control system actuates control surfaces and thrusters to meet these objectives, while passing information on the position, speed and heading to the backseat driver.

The chosen backseat driver for this application is Mission Oriented Operating Suite (MOOS-IvP), which is an open source, autonomy middleware developed by MIT and Oxford. MOOS-IvP has two main parts: MOOS and the Interval Programming (IvP) Helm. MOOS is based in a publish/subscribe architecture where all processes produce or receive information from a common point, the MOOS database (MOOSDB). 5] These processes are run through separate threaded applications. The IvP Helm is a key MOOS application that implements autonomy using a behavior-based architecture. Behaviors are distinct software modules that deal with specific aspects of autonomy. Behaviors may be deterministic, for example “waypoint navigation”, “loiter”, and “station keep” or non-deterministic, for example, “avoid contacts” or “keep fixed distance” etc. Non-deterministic behaviors run concurrently with deterministic ones, each producing an objective function. Objective functions are surfaces over the axes of heading and speed (and possibly depth for AUVs) and are provided at regular intervals to a solver that determines the optimal course of action. [5]

A simplified architecture of the proposed implementation is shown in Figure 1. The red rectangles represent new MOOS applications and behaviors, the blue shapes represent preexisting MOOS architecture, the purple rectangle represents a non-MOOS application, the yellow cylinder represents a non-MOOS database and the green hexagon represents a database containing the raw ENCs.

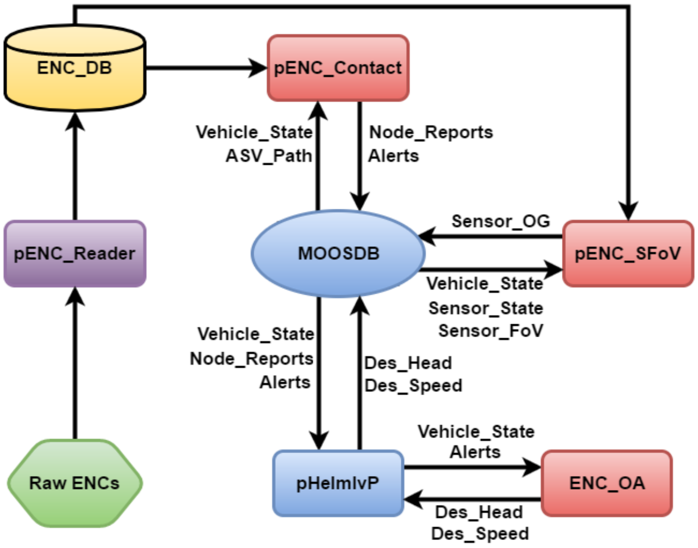

Figure 1: Simplified Architecture for Chart Awareness

pENC_Reader reads a raw nautical chart and converts it to database suitable for real-time query. pENC_Contact monitors ASV’s position and produces alerts when obstacles are in close proximity to the ASV. ENC_OA is a new IvP-Helm behavior that implements object avoidance based on these alerts. pENC_SFoV calculates which obstacles should be within a sensors field of view and publishes these to MOOSDB for use by sensor applications. These processes are described in detail below.

ENC Reader

The goal of the MOOS application pENC_Reader is to read the raw ENC files and convert them to an easily accessible database, ENC_DB, with the latitude, longitude, obstacle type, and threat level for each obstacle. The ENC_DB will allow the ASV to preemptively filter unnecessary information from the ENC and give the ASV the ability to quickly query the database in real time to identify potential hazards to the ASVs navigation.

Many of the features in ENCs do not have recorded depths. For example, in the nautical chart for Portsmouth Harbor, NH, there are 201 underwater rocks and only 54 have recorded depths. In this case, the depth of the obstacle has to be inferred from the Water Level (WATLEV) attribute, which gives a qualitative description of the depth of an object. Table 1 correlates the WATLEV ID numbers to the effect of the surrounding water on the object.

	1	**2**	**3**	**4**	**5**	**6**	**7**
WATLEV	Partly submerged at high water	Always dry	Always underwater	Covers and uncovers	Awash	Subject to inundation or flooding	Floating

Table 1: Descriptions of WATLEV ID numbers

To address the issue of not always having quantitative descriptions of an objects depth in an ENC, a “threat level” attribute for each obstacle is defined using both the qualitative and quantitative descriptions of object’s depths. Table 2 describes the proposed threat levels where depths (Z) are in meters, negative depths are above the surface, and WL is the Water Level ID as defined in Table 1.

Threat Level	**Depth (m)**	**Water Level ID**	**Description**	**Desired Reaction**
5	---	---	Land, docks, dams, wharfs, pontoons, and dykes	Slow down and avoid running ashore
4	$Z \leq 0$	WL = 1, 2, 5, 7	Will hit obstacle	Slow down and avoid obstacle quickly
3	$0 < Z \leq 1$	WL = 4	Close to hitting obstacle	Slow down and avoid obstacle
2	$1 < Z \leq 2$	WL = 3	Somewhat close to hitting obstacle	Slow down and avoid obstacle slightly
1	$2 < Z \leq 3$	WL = 3	Not close to hitting obstacle	Slow down
0	$Z > 3$	WL = 3	Will not hit obstacle	Do nothing

Table 2: Description of Obstacle Threat Level

The threat level is determined by ENC Reader and stored within the ENC_DB for easy retrieval by pENC_Contact.

ENC Contact

The MOOS application pENC_Contact searches for obstacles in the ENC_DB within a “search polygon” around the desired path. This application will subscribe to the planned path and the ASV’s location, speed, and heading. The size and shape of the search polygon is dependent on a predetermined maximum search radius and the speed and size of the ASV. This application will not determine the next state for the vehicle, but will instead publish alerts to the MOOSDB that will include the latitude, longitude, threat level and type of each obstacle in the search polygon.

Figure 2 shows an example in which pENC_Contact will look in an expanding zone for obstacles around the nominal path (shown in yellow and red, respectively). If there are any obstacles in path of the ASV or in the Search Zone, pENC_Contact will publish variables containing the position, threat level and type of each obstacle to the MOOSDB. This information will be used later in the Obstacle Avoidance procedures.

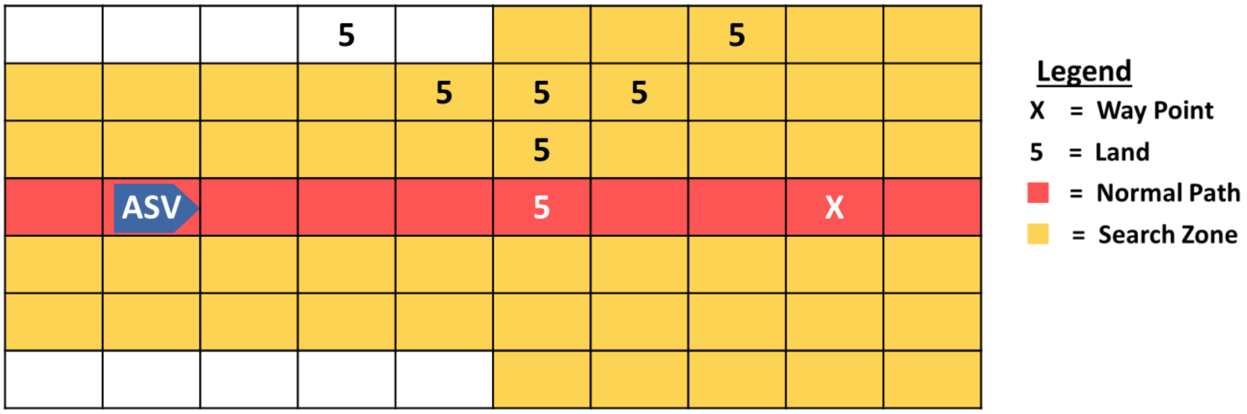

Figure 2: ENC Threat Detector Search Zone

Obstacle Avoidance

A new IvP Helm behavior has been developed, ENC_OA, to react to obstacles near or inside the path of an ASV. Using the threat detection alerts published by pENC_Contact, ENC_OA makes speed and heading decisions based on the obstacles identified in the search polygon.

There are three basic zones for ENC_OA: the Slow Zone, Warning Zone and Prohibition Zone. The size of each zone is dependent on the threat level of the obstacle as well as the size and current speed of the ASV. A desired reaction for this behavior is shown in Figure 3. As the ASV reaches the green Slow Zone, the ASV should begin to slow to a safe speed. Once the ASV moves into the yellow Warning Zone, the ASV will make evasive actions around the red Prohibition Zone. ENC_OA treats the Prohibition Zone as a collision between the ASV and the obstacle.

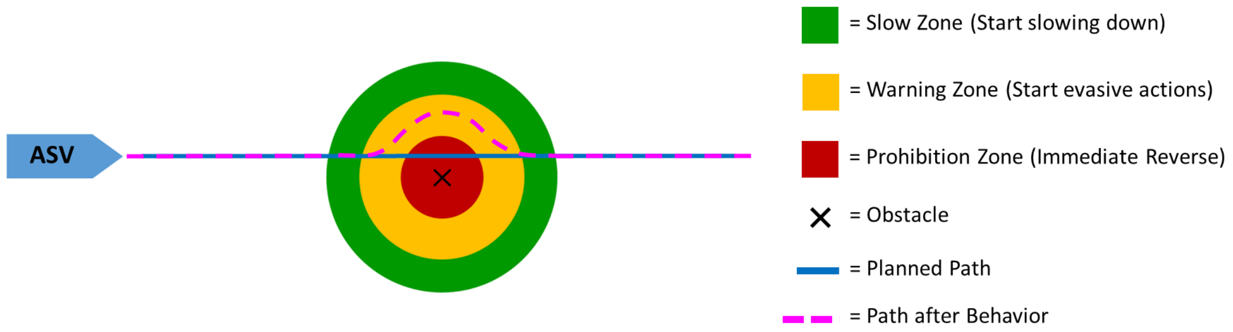

Figure 3: Desired reaction for the OA behavior

In MOOS, the planned path is defined by a waypoint behavior that creates an objective function represented as a surface in polar coordinates, whose peak corresponds to the optimal heading and speed. An example objective function for the waypoint behavior is shown in Figure 4. To avoid an obstacle found using pENC_Contact, ENC_OA creates an objective function which penalizes heading choices in the direction of the object. The amplitude of the penalty is given by the equation:

$$Cost(angle\ to\ obstacle) = \frac{(Threat\ Level\ of\ Obstacle)}{(Distance\ to\ obstacle)} * Priotity\_Weighting$$

The objective functions for ENC_OA and the waypoint behavior are combined in the IvP Helm Solver to determine the desired heading and speed to provide a safe path for the ASV.

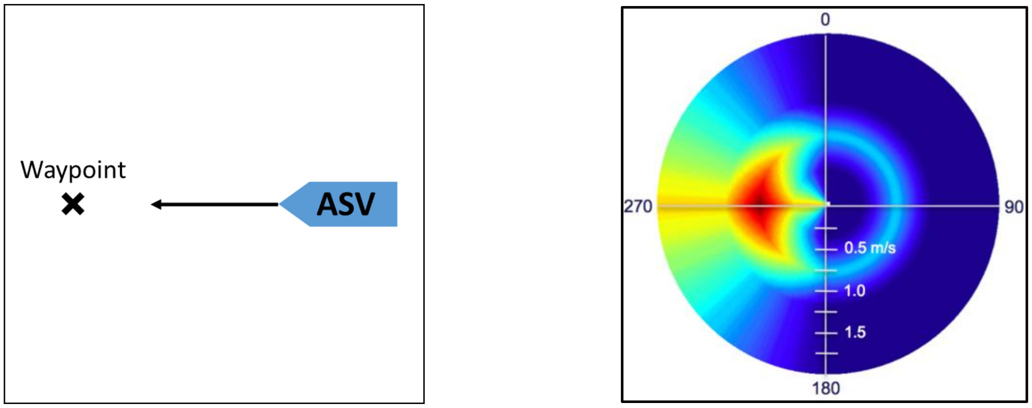

Figure 4: Waypoint objective function defined over the possible heading and speed values. The favored values are the ones that point 270 degrees from the vehicles position and in the middle of the range of possible speeds.

Results

Currently, both pENC_Reader and pENC_Contact have been implemented and tested in MOOS's simulation software (Figure 5) with the search polygon for pENC_Contact simplified to a square centered on the ASV's current position. In the left image of Figure 5, the ASV is shown following its planned path with no environmental awareness. In the middle image, pENC_Reader has been implemented providing land areas (black lines), and obstacles (points) from an ENC. Orange points are obstacles of threat level 3 and green points are obstacles of threat level 0. In the right image, pENC_Contact dynamically identifies which obstacles might pose a threat to the ASV. The red box is the search polygon and blue circled dots are obstacles that were found within it. The key information (latitude, longitude, threat level and type of obstacle) for each of these identified obstacles are published to the MOOSDB at regular intervals for use in ENC_OA.

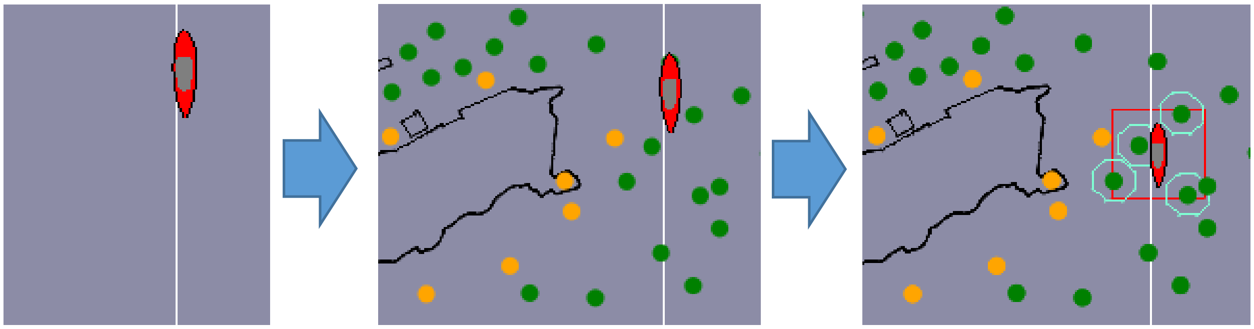

Figure 5: Progression of knowledge of environment using this architecture (Left – no knowledge from ENCs, Middle – using only pENC_Reader, Right – using pENC_Reader and pENC_Contact) where the white line is the planned path, the black lines are land, the red box is the search area, the orange points are obstacles of threat level 3 and green points are obstacles of threat level 0

Once pENC_Contact has determined the potential threats and published alerts containing the information on these obstacles to the MOOSDB, ENC_OA will use these alerts to create an objective function for heading and speed. Creation of the heading objective function has been simulated in MATLAB and is illustrated in Figure 6. However, the speed objective function has not yet been simulated. The left image of Figure 6 provides a plan-view of a complex scenario (which while possibly unrealistic, is useful for illustration purposes) in which the ASV's planned path, shown as the white line, goes directly through multiple obstacles of threat level 3. In the right image the blue line shows the corresponding heading objective function for ENC_OA and the red line is the ASV's current heading. The most desirable heading is indicated when the OA Utility function, shown in the radial axis, is 1. In this situation the ASV should deviate from its desired path and turn towards starboard to avoid the obstacles.

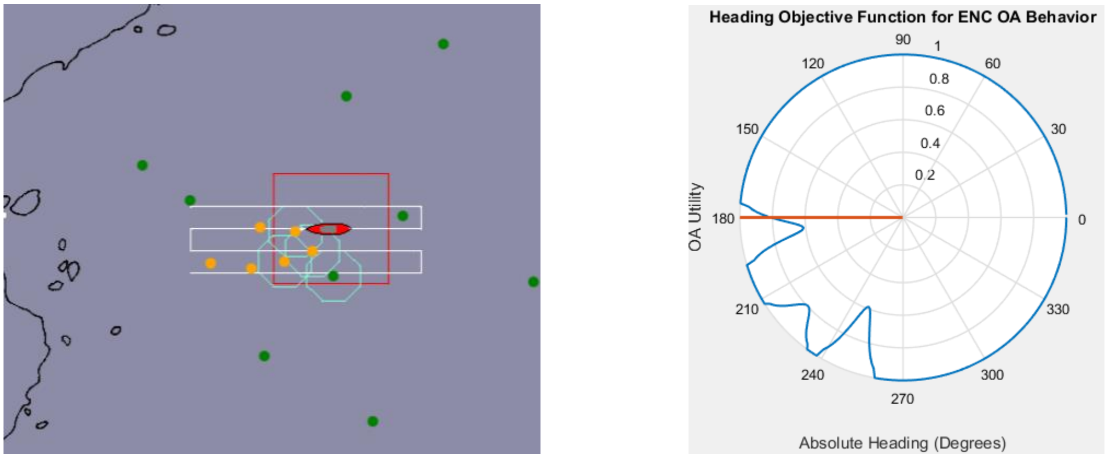

Figure 6: Example showing the objective function for ENC_OA (Left – Screenshot of simulated mission, Right – Graph of the objective function for ENC_OA) where in the left image the black lines are land, the red box is the search area, the orange points are obstacles of threat level 3 and green points are obstacles of threat level 0 and in the right image the blue line shows the corresponding heading objective function for ENC_OA and the red line is the ASV's current heading

Figure 7 uses the same scenario as Figure 6 and shows how the desired heading can be calculated by a weighted sum of the heading utility functions of ENC_OA and the waypoint behavior in the IvP Solver. The left image shows the heading objective function for just the waypoint behavior, the middle shows the heading objective function just for ENC_OA and the right shows the combination of the two heading objective functions with the new desired heading shown by the red line. This last image simulates the IvP Solver with the desired heading shifting towards starboard away from the obstacles as expected.

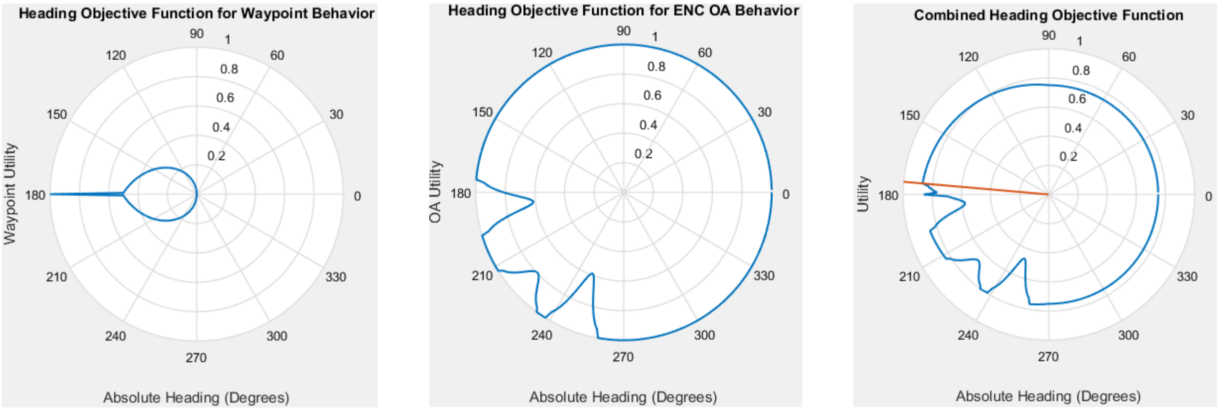

Figure 7: Example showing a Matlab simulation of the combination of the waypoint and obstacle avoidance behaviors (Left – The objective function for the waypoint behavior, Middle – The objective function for ENC_OA, Right – The combined objective function of both the waypoint and ENC_OA behaviors

Conclusions

Static mission planning is a major issue for ASV feasibility, especially in hydrographic applications. Using ENCs to give an ASV awareness of its environment alleviates many of the issues with static mission plans by allowing the ASV to dynamically change its path in situ based off static objects found in an ENC and by giving context to sensor measurements that are subject to uncertainty.

Our implementation will combine Larson's use of ENCs for obstacle avoidance with Elkins' use of nautical charts for context for sensor measurements along with advanced path planning into a single package.

As shown in the simulation above, providing an ASV the ability to read, understand, and use nautical charts has the potential to significantly increase their level of autonomy. This added autonomy allows the ASV to safely react to obstacles in its environment as well as decreasing planning time and the risk of human error during path planning.

References

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Sam graduated from the University of New Hampshire in 2015 with his BS in Electrical Engineering. Currently he is working on his MS in Electrical Engineering at University of New Hampshire. For his Masters research, Sam is working on nautical chart aware autonomous surface vehicles for the Center for Coastal and Ocean Mapping.

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