Advances in Autonomous Obstacle Avoidance for Unmanned Surface Vehicles

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ABSTRACT

The Space and Naval Warfare Systems Center, San Diego has been involved in the continuing development of obstacle avoidance for unmanned surface vehicles (USVs) towards the aim of a high level of autonomous navigation. An autonomous USV can fulfill a variety of missions and applications that are of increasing interest for the US Navy and other Department of Defense and Department of Homeland Security organizations. The USV obstacle avoidance package is being developed first by accurately creating a world model based on various sensors such as vision, radar, and nautical charts. Then, with this world model the USV can avoid obstacles with the use of a far-field deliberative obstacle avoidance component and a near-field reactive obstacle avoidance component. This paper addresses the advances made in USV obstacle avoidance during the last two years.

Keywords: robotics, unmanned surface vehicle, USV, autonomous, obstacle avoidance, OA, path planning, reactive

1 Introduction

The Space and Naval Warfare Systems Center, San Diego (SSC San Diego) has been developing the technologies for autonomy on unmanned surface vehicles (USVs) with the purpose of providing more autonomous functionality and reducing the reliance upon operator oversight. More specifically, the current focus is to create a robust obstacle avoidance capability and then move on to more advanced behaviors such as autonomous recovery in the case of lost communications, target tracking and/or interception, collaborative behaviors, etc.

1.1 Previous work

SSC San Diego has been involved in the development of autonomous vehicles for over 25 years. Previous work in the UGV arena has been transitioned into the USV world such as waypoint navigation, perception sensors, and obstacle avoidance (OA) techniques. In the paper by Larson, Bruch, and Ebken[1], SSC San Diego demonstrated a deliberative far-field path

planner capable of avoiding both stationary and moving obstacles. This approach was not designed to provide an optimal solution, but a fast and efficient method for avoiding most obstacles. At the time of the publishing of that paper, no near-field reactive control had yet been implemented on the USV.

1.2 Overview of project

Over the last two years SSC San Diego has primarily focused on the research and development of the reactive obstacle avoidance component of the USV with many advances made in near-field collision avoidance, sensor fusion, machine vision, and control theory. Progress has also been made in the deliberative planning area.

Figure 1. SSC San Diego USV test platform

2 Obstacle Avoidance

For an autonomous vehicle to succeed at advanced maneuvers, a solid baseline of obstacle avoidance is mandatory. Such a capability requires an accurate world model, utilizing maps and sensors, and a robust technique to avoid those obstacles in the model. The avoidance technique used here is a two-tiered approach consisting of a deliberative or far-field model and a reactive or near-field model.

2.1 World Model

To successfully avoid obstacles, a robotic vehicle has to first have an accurate model of the world in which it is operating. SSC San Diego is using a 2-D obstacle map called an occupancy grid, which is created by dividing the environment into a discrete grid and assigning

each cell location a value representing the probability of being occupied by an obstacle. For the USV, this environment is separated into two levels. The first level is a large overview map, spanning a greater distance but with a lower resolution of data. This model is created using digital nautical charts (DNC), automated radar plotting aid (ARPA) contacts, and automatic identification system (AIS) contacts. The moving ARPA and AIS contacts are represented in the model using a projected obstacle area and are located by the closest point of approach (CPA) calculation results. The second level consists of a much smaller area in the immediate vicinity of the USV and is populated with data from sensors that have a limited range such as monocular and stereo vision, while also using other sensors like radar and nautical charts.

a   b
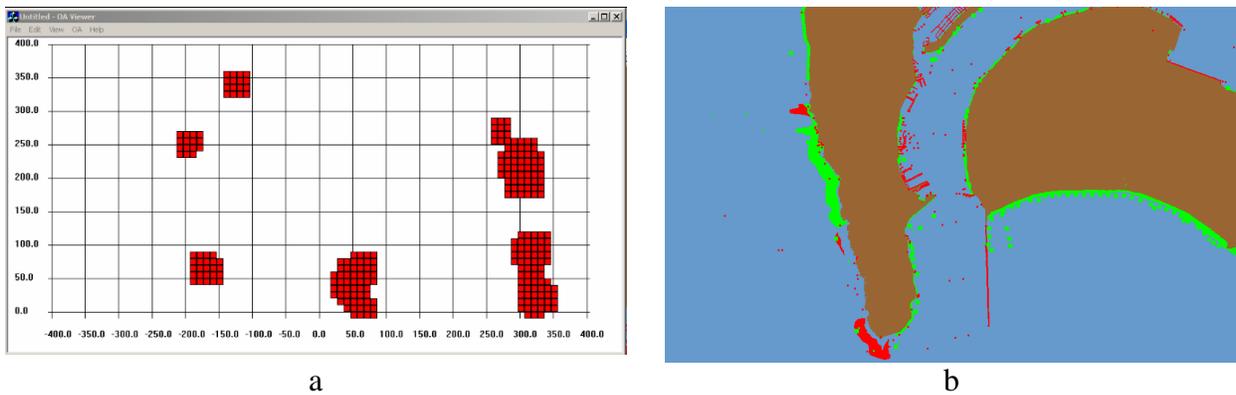
Figure 2. World model obstacle maps used by the reactive OA (a) and the deliberative OA (b)

2.2 Deliberative

Deliberative OA involves the planning of routes around stationary and moving obstacles in the far-field, or beyond a certain distance from the vehicle, while attempting to maintain the original user-defined route or end goal. An important aspect of autonomous piloting in a complex harbor environment is that the USV must follow designated nautical rules of the road while avoiding obstacles. The toolset developed for deliberative OA can also be applied to the problem of target interception and tracking.

2.21 Rules of the Road

Previously, SSC San Diego demonstrated a real-time deliberative path planner to avoid moving obstacles, which used a limited sense of navigation rules defined in the 1972 International Regulations for Preventing Collisions at Sea (72 COLREGS[2]), specifically those

that included avoiding collisions. These navigation rules are a system of regulations governing many aspects of maritime navigation, including multi-ship maneuvers for collision avoidance. Recently, the deliberative OA component was augmented with a new rule-based approach in the path planner to follow the rules of the road during all stages of planning. This new approach handles three basic maneuvers for collision avoidance between vessels (paraphrased):

1.   Any vessel overtaking another vessel shall keep out of the way of the vessel being overtaken. The passing vessel should pass on the port side of the other vessel, unless she sounds an audible whistle signal, and may then pass on the starboard side.

2.   When two power-driven vessels are meeting on reciprocal courses (head on), each shall alter course to starboard so that each shall pass on the port side of the other.

3.   When two power-driven vessels are crossing, the vessel that has the other on her starboard side shall keep out of the way and avoid crossing in front of the other vessel.

These rules are deliberately vague with respect to the angles and ranges for which they apply. A large amount of human intuition and experience is expected to fill in these and other gaps in the COLREGS. Two small and easily maneuverable craft may be perfectly safe at much closer ranges for example, whereas two oil supertankers must maneuver much earlier to ensure safety. To apply these rules to the USV, such details must be exhaustively supplied. The parameters have been determined for a craft of the size and maneuverability of the USV through experience and testing.

The determination of whether a series of waypoints can be followed while obeying the COLREGS is made by analyzing the route for the points of closest approach with other vessels based on their course and speed with respect to the USV's planned motion. The rules are evaluated at these closest points of approach in the following manner (with an imposed constraint that the USV should not approach within 50m of another ship):

1. Overtaking: If the USV is moving at a higher velocity and the two vessels are moving at the same heading within 45 degrees and approach within 200m, then the other vessel should be on the starboard side of the USV.

2. Meeting: If the two vessels are moving at the opposite heading within 45 degrees and approach within 200m, then the other vessel should be on the port side of the USV.

3. Crossing: If the other vessel is moving along a heading that is between 45 and 135 degrees greater than the USV and approach within 200m, then the closest point of approach should occur on the port side of the USV. (i.e. the USV should pass astern of the other vessel). The reciprocal case places the responsibility on the other vessel to avoid the USV and is therefore not given a specific rule.
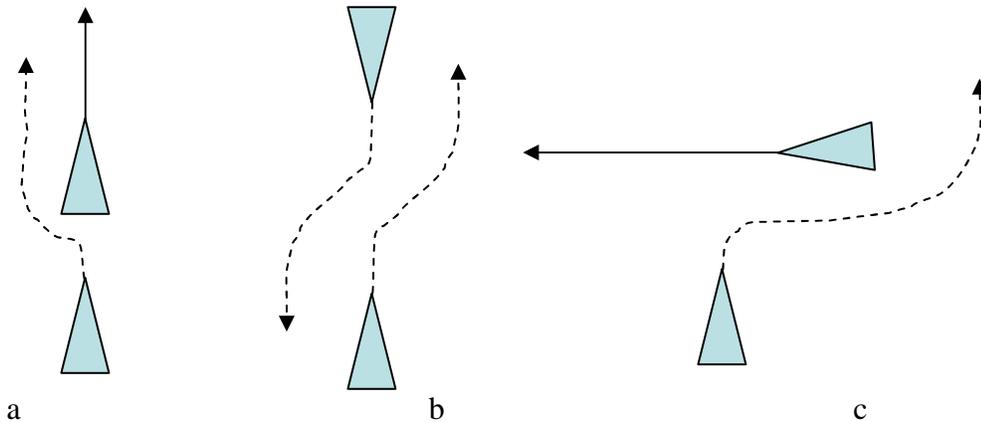
Figure 3. Navigation rules of the road approaches to avoid collisions for overtaking (a), meeting (b), and crossing (c)

These rules are more complex to plan than typical obstacle avoidance tasks. The USV can be in a violation position at a range within 200m from another vessel, but if the current path is correcting the condition such that the closest approach is in accordance with all of the rules, then there is no violation. This makes it somewhat difficult to design heuristics that do not sacrifice completeness when considering which portions of the search space to prune. Techniques used by Benjamin, Curcio, and Leonard[3] completely rely upon reactive behavior-based control to enforce the COLREGS using interval programming to find optimal actions. It is SSC San Diego's desire to communicate full paths back to the user for situational awareness and feedback. This requirement drove the work towards a design that provides a complete plan to the goal. Planning over the entire space also helps prevent the USV from entering box-canyon situations that purely reactive approaches often suffer from. Techniques such as dynamic

programming could be used to avoid costly re-computation of search states, but there are many control options which give rise to a large branching factor and a relatively low density of explored states. It is for these reasons that *randomized* search techniques such as Probabilistic Roadmaps[4] as well as Genetic algorithms and Markov Chain Monte-Carlo techniques[5] have been explored. These techniques all take advantage of the ease with which each of the rule conditions can be evaluated on complete paths and the latter two take advantage of heuristic techniques for proposing better paths, while Probabilistic Roadmaps must still perform a brute force search.

Future enhancements in this area could lead to the use of lights and horns during these avoidance maneuvers in accordance with the navigation rules.

2.22 Target Tracking

SSC San Diego has completed initial development of target tracking and/or interception for the USV, which uses the deliberative OA component to change its course and velocity to approach the target while avoiding other stationary or moving obstacles. Future developments will add a new behavior to the reactive component to complete the final action requested of the USV (pull up on the port or starboard side, trail behind, cut-off and stop a target, etc.).

2.3 Reactive

The near-field component of the two-tiered approach, also known as reactive OA, reacts to short-range obstacles, somewhere within 400m of the USV. The USV avoids these obstacles by modifying the throttle and steering commands in real-time based on the combined votes of each behavior. The SSC San Diego implementation of reactive OA is a behavior-based common world model approach. That is to say, all of the near-field sensors are fused into a common local world model, and individual behaviors vote on specific navigation solutions within that model. For instance, the obstacle avoidance behavior votes for actions that avoid or turn away from potential hazards while the path-following behavior votes for actions that will keep the vehicle on the planned path.

This approach is not novel but has a long history of applications in real-world systems (including the Mars Rovers) and has its lineage back to the Carnegie Mellon University Morphin

6

algorithm[6] and Distributed Architecture for Mobile Navigation (DAMN)[7]. As applied here, a number of arcs are projected in front of the vehicle over the local world model obstacle map (Figure 4). The number of arcs considered is a function of the map size and grid spacing, with the arcs spaced such that one arc passes through each of the outer cells. This approach guarantees that each cell in the grid is covered by at least one arc so that all navigable paths are considered. Each of the arcs is related to the vehicle velocity and turn-rate by ($V=R/\theta$) where R is the radius of the arc, V is the vehicle velocity, and θ is the vehicle turn-rate. More detail of this voting technique can be found in [1].
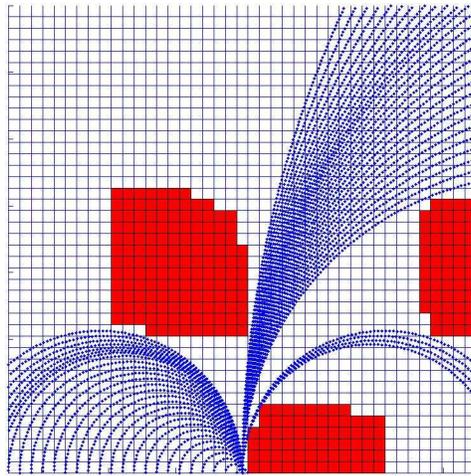
Figure 4. Reactive world model with obstacles and possible arc paths

While implementing this reactive obstacle avoidance component on the USV, there were a few issues that needed to be addressed. The following describe some of these and their solutions.

Initially there existed a disconnect between the commands that were being sent and the actual steering of the USV because the commands did not account for environmental factors such as wind, current, or even an unbalancing of the boat. A feedback control loop was implemented to ensure the selected arc on the reactive OA was executed accurately regardless of the environment or other physical conditions. A KVH gyroscope (maximum reporting angular rate at 100 Hz) was added to report turn-rates, which were then integrated into a PID loop for steering auto-correction.

Test results showed that occasionally the output from the arbiter, the decision-maker of the reactive component, fluctuated between steering to the left and right side of an obstacle, approaching a near-collision. This was due to the combination of votes from a path-following behavior and an obstacle avoidance behavior; a turn to the left would move the path-following vote to the right, to return to the path, and increase the overall vote to the right, which could eventually earn the highest vote and change the course of the USV. A simple solution of decreasing the overall vote for all possible vote bins on the opposing side of an obstacle, relative to the USV, made it more difficult for the vehicle to switch directions and cross over in front of obstacles.

During testing, it was also discovered that as obstacles moved past the vehicle and out of the obstacle grid, the USV would at times turn sharply in an effort to return to the route, turning directly into the obstalce. The obstacle arc grid used by the reactive obstacle avoidance program uses only the forward-looking half of the environment (i.e. that which is in front of the vehicle), leaving out obstacles sometimes only meters away, just because they were behind the vehicle. For extremely quick turns however, it is important to have knowledge of obstacles that are close behind the vehicle. In the near future a more complete near-field world model will be developed but in the interim, to mitigate problems, the data in the rows just behind the USV are mirrored up to the current horizontal plane, eliminating those sharp turns which would lead into obstacles.

a   b
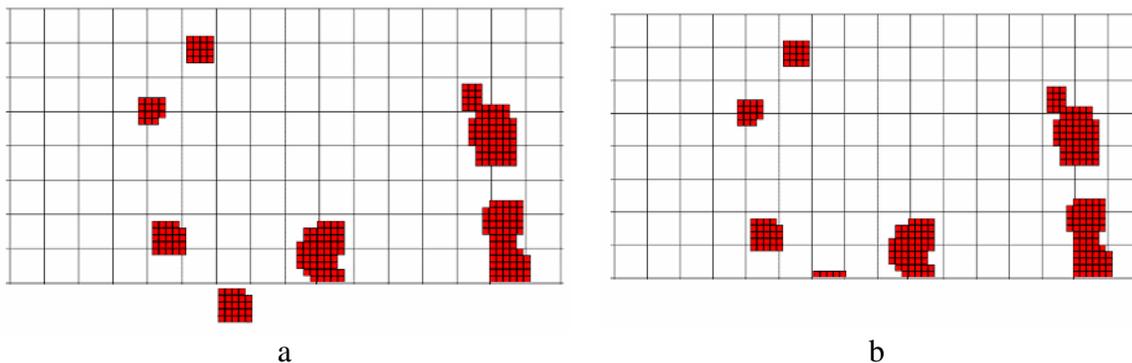
Figure 5. Reactive world model showing the placement of an obstacle off the map and behind the vehicle (a) and the resulting mirrored obstacle onto the map.

Because of the drag properties on the sea surface and the variability in the control of a USV's rotational speed, it was no uncommon for the USV to slightly drift sideways into the obstacle area (or the grown area representing an obstacle), causing the USV to evoke emergency procedures to return to open water. This was addressed by modifying the characteristics of the free space voting behavior by decreasing the values of the votes near the obstacles, creating a buffer around obstacles, and giving more priority and more voting value to the arcs that are slightly farther away from the obstacle areas.

a   b
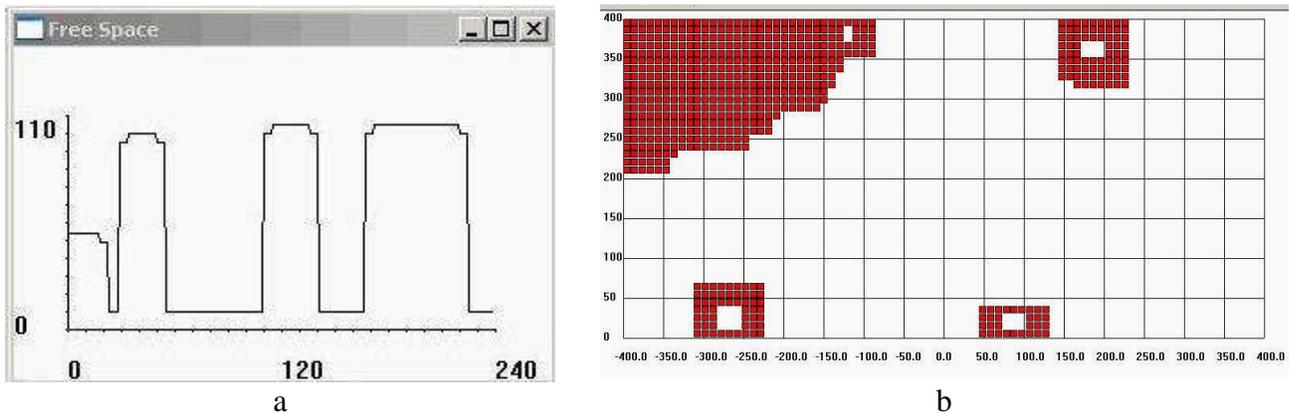
Figure 6. Free space voting behavior with decrease in value for near-obstacles (a) and the corresponding obstacle map (b)

3 Sensors

In order for the USV to navigate autonomously in the environment in which it operates it is critical that an accurate world model be developed. The development of that model requires the use of multiple types of sensor systems to provide overlapping coverage areas in multiple spectrums and with a variety of processing techniques. SSC San Diego is using and has added improvements to several advanced sensor technologies including monocular and stereo vision and digital marine radar systems.

3.1 Monocular Vision

SSC San Diego is developing a monocular vision solution to compliment the NASA Jet Propulsion Laboratory (JPL) stereo vision system currently in use. The method determines the range to an obstacle using the horizon distance as a baseline. It relies on well-known geometries of the Earth and a single digital imager. At sea, the distance to the horizon can be estimated with

9

knowledge of the Earth's radius and the height of the camera above the water. This distance, coupled with a measurement of the relative angle between the horizon and the waterline of the obstacle, permits a rough trigonometric calculation of range as illustrated in figure 7. In the presence of a shoreline instead of a sky-water horizon, nautical charts provide an analogous baseline distance to the shore and a similar ranging calculation is performed.
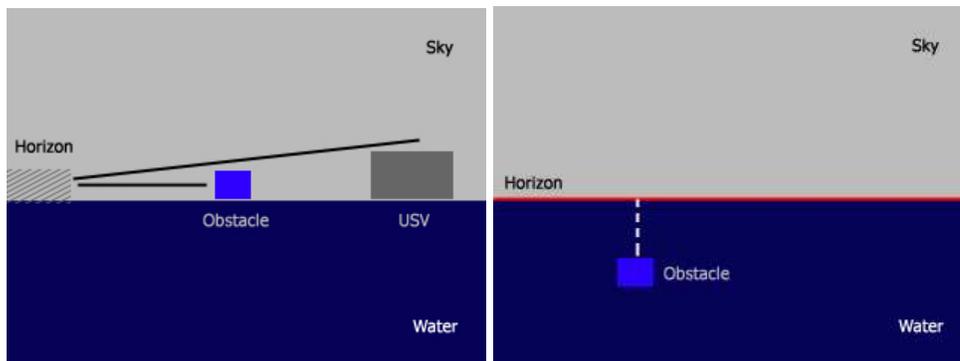
Figure 7. Trigonometric calculations of range of an obstacle

In reality, however, important technical challenges are obscured by this simplistic explanation. Chief among them is the automation of real-time horizon and obstacle-waterline estimation. SSC San Diego has achieved reasonably good horizon estimation by applying a Hough-transform-based line detector to median filtered scenes on a frame-by-frame basis. Methods are being explored to further improve the algorithm by applying multiple-frame tracking techniques.

The segmenting of obstacles and the estimation of the waterline is a very difficult computer vision problem due to the dynamics of the lighting conditions and the ocean surface background as well as other environmental factors. Employing multi-frame point correspondences and region-growing techniques has provided encouraging results. Several other methods have shown promise and are being explored. More specifics this monocular vision obstacle-detection and ranging solution will be described in a forthcoming paper.

Figure 8. Monocular vision snapshot showing horizon (coastline) and obstacle detection and ranging

3.2 Stereo Vision

SSC San Diego has continued to work with the NASA Jet Propulsion Laboratory (JPL) on stereo vision-based perception for the USV. JPL has used stereo vision on the Mars Rovers and SSC San Diego has transitioned some of that technology to their unmanned ground vehicle (UGV) programs [8]. Similar image processing and obstacle detection algorithms have been tested on the USV with very promising initial results. Figure 9 shows an example of one stereo vision frame and subsequent processing. The frame on the left has multiple sub-frames consisting of: false-color range data (upper left) where near pixels are in red and far pixels change to purple, false-color elevation data (upper right) where lower pixels are green and higher pixels change to purple, a top-down view of the 3-D point cloud data (center), and a profile of the point cloud data along the line leading from the USV to the sailboat (bottom). Notice how well the sailboat stands out in the profile at the bottom of the image. On the right-hand-side of the figure is the original image overlaid with colored pixels to indicate its traversability. The green areas have been deemed traversable and pink areas represent obstacles. In this image three vessels are detected as obstacles; a sailboat at 100m, a medium-sized fishing vessel at 480m, and

11

a Navy warship at 900m. This 3-D obstacle data is collapsed into a 2-D occupancy grid as described in section 2.1.
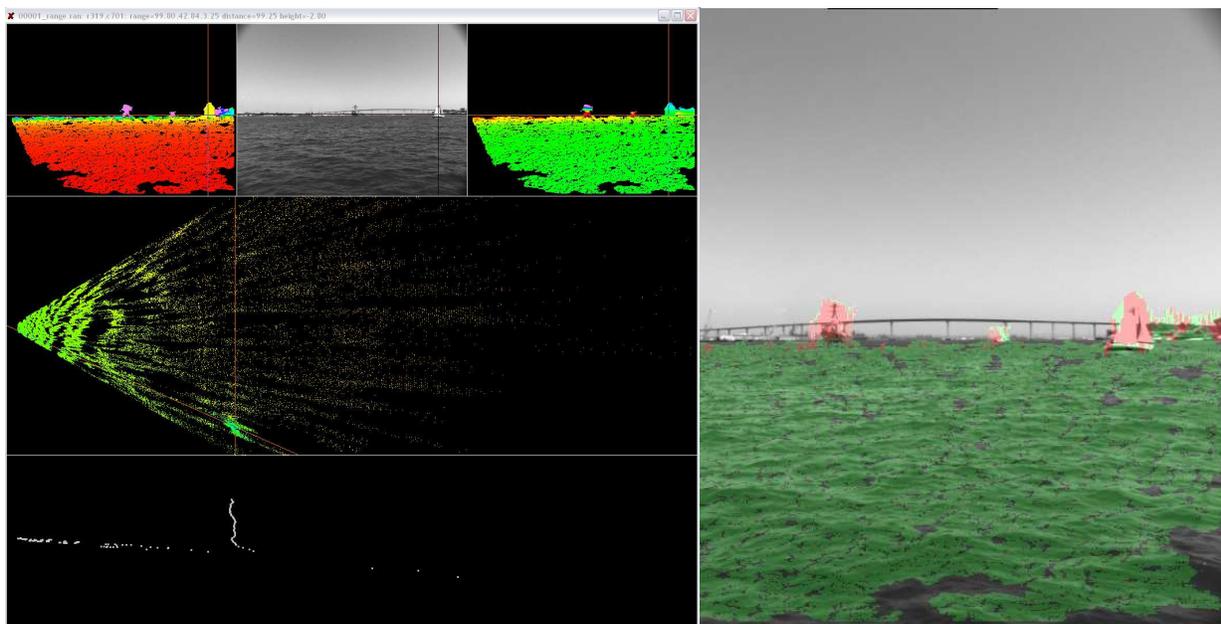
Figure 9. Stereo vision and obstacle detection data set

Plans are in place and work will begin soon on methods to further exploit the stereo vision data and imaging systems. These methods will make use of the color and texture features in the image. By using the stereo vision data to determine what the water generally looks like in areas where no obstacles are present it should be possible to more easily identify those areas where there are obstacles. This will be an important addition because simply analyzing the 3-D profile of the data will not always reveal low-lying obstacles.

3.3 Radar/AIS

The radar system on the SSC San Diego USV is a standard marine radar (Furuno) with a third-party PC controller developed by Xenex Innovations Ltd., which provides a digital networked interface for the radar. The Xenex system provides an SDK to access the radar data and controls. A radar server application has been developed utilizing the Xenex API to customize access to the radar. Included with all the standard radar controls and scan data is access to the Xenex Advanced Radar Plotting Aid (ARPA) data set and controls, which provides algorithms to automatically acquire and track up to 100 contacts.

One challenge with the radar is that for a small highly maneuverable boat, the turn-rate can approximate that of the radar itself. During high turn-rate maneuvers, the radar is either turning much faster or slower than normal, relative to earth, and the data is therefore skewed. When this occurs most often the contacts are lost until the USV returns to a relatively straight trajectory. Multiple approaches to mitigate these effects are currently under investigation. The first key to handling the case of high turn-rates is to generate accurate scan images (360 degree polar plot). Placement of the radar scan data in the correct geographical location corresponding to the radar's heading at the time of each scan line's acquisition is the goal. The current radar provides 1024 segments (slices) of data per revolution. Creating the best real-world representation of a full radar scan data set as to the USV's environment requires knowing the USV heading changes during a single scan and registering the heading and/or changes. The faster the heading updates, the more accurate the final data set will represent the objects seen by the radar. The Xenex application has been improved from 2 to 10 Hz in this regard. The complete benefit of the increased heading rate is still being quantized. Even faster heading updates are possible with the Xenex processor and the use of a complete Furuno system may allow for 40 Hz updates.

A complete Furuno system being considered not only provides faster heading updates to improve target location but also provides increased scan resolution (8192 scan lines per revolution) and the option to increase the antenna rate to 42 rpm from the current 24 rpm. All of these increases should help provide a more detailed and accurate description of the radar image about the USV, including during more dynamic maneuvers.

Xenex is also working on a next-generation controller which is due out later this year with improvements similar to the integrated Furuno system with support for higher rpm antenna rates and with the possibility to increase heading update rate.

3.3.1 Reactive Radar Images

In the reactive component, the radar provides the radar return image data (after video threshold, video reference, and video negative values have been applied). The radar return is, in essence, a ready-made obstacle map. In an ideal radar image, only obstacles on the water or the

shoreline show returns. The radar data is converted from the polar scan format to the Cartesian obstacle-grid representation and fused with the other sensor data. Of course, the real-world data is never ideal and often contains noise. In the current configuration, the Furuno-Xenex control leaves the returned radar data with a disk of sea-return back scatter extending from the center out to about 100 yards, which cannot be electronically suppressed. With proper control settings, however, the background can be subtracted in this region from signal and track obstacles (e.g. buoys) up to close ranges of about 30m. Under ideal conditions (calm waters) radar data processing has been developed that produces a reliable obstacle map out to at least 200m for collision avoidance of radar-perceived objects. The processing algorithms required to maintain obstacle tracking are being developed for less than idea conditions (e.g. swells, wakes, wind, etc.). The radar's own "Sea Clutter" control can help here, as well as some smart filtering of both the data spatially and temporally. The radar obstacle map is dead-reckoned between completed radar sweeps based on the USV's movement so that the reactive component is provided updated obstacle maps at a rate of 10 Hz.

4 Conclusions

SSC San Diego has made significant advances in the autonomous navigation and obstacle avoidance capabilities of its USV. The current design is routinely tested in San Diego Bay where the methods described here are shown to provide a high degree of success in avoiding dynamic and static obstacles. More work is required on the sensor systems and associated processing algorithms to provide a more accurate world model in both the far and near fields.

5 Acknowledgments

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