Autonomous Mission Planning and Execution for Unmanned Surface Vehicles in Compliance with the Marine Rules of the Road

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This is to certify that I have examined this copy of a master's thesis by

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Abstract

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In order to achieve a high level of autonomy in a highly dynamic and unpredictable world, reliable obstacle avoidance is required to ensure the safety of other vessels, people, and property. Discussed here is the integration of the Coast Guard International Regulations for Avoiding Collision as Sea (COLREGS), or the "Marine Rules of the Road", with an autonomous mission management software. The result provides deliberative obstacle avoidance capability, that complies with the COLREGS, to an Unmanned Surface Vehicle. The avoidance algorithms are implemented in an evolutionary path planning system. The planner uses nearby vehicle information and digital nautical charts to plan compliant paths. Both Head-On and Crossing collision scenarios are considered. The planner is capable of dynamically replanning paths based on updated environmental information.

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GLOSSARY

AFSL: Autonomous Flight Systems Laboratory

AIS: Automatic Identification System

ARPA: Automatic Radar Plotting Aid

COLREGS: United States Coast Guard International Collision Regulations

DEM: Digital Elevation Map

ECoPS: Evolution-Based Cooperative Planning System

IED: Improvised Explosive Device

ISR: Intelligence Surveillance and Reconnaissance

NGS: National Geospatial-Intelligence Agency

NMEA: National Marine Electronics Association

NMEA 0183: ASCII serial communication protocol, published by NMEA, for communication among marine electronics components.

RIB: Rigged-hull Inflatable Boat

UAV: Unmanned Aerial Vehicle

USV: Unmanned Surface Vehicle

UTC: Coordinated Universal Time - Also known as Greenwich Mean Time

UUV: Unmanned Underwater Vehicle

Agent: A member of our team of vehicles.

Collision Cone: A geometric based, mathematical condition, that uses relative motion of a point and a circle, to determine if a moving point is on a course to intersect any point in a moving circle.

Committed Trajectory: The waypoints or heading rate commands that have been sent to the guidance system.

Fitness: A performance measure of how well a path complies with mission objectives.

Port Vector: The vector that points to an obstacle's port side.

Rule Range: The maximum distance to an obstacle for which we apply the rules of the road.

Spawn Point: The location the path planner uses for the start of paths. When our vehicle gets to this location a new trajectory is committed to the guidance system.

Stern Vector: The vector that points to an obstacle's stern.

$C(Q(s_p))$: Cost function for a path, Q, from the start point until the endpoint.

$\Delta\theta$: Difference between heading of our vehicle and that of the obstacle.

J: Objective function for a candidate path.

N_T: Number of tasks in a mission scenario.

r: Range to obstacle.

R: Safety radius around the obstacle.

$R_i(N)$: Score of a candidate path from the start point of the path until the endpoint of the path.

$R_i(s_p)$: Score that the vehicle has attained prior to the next spawn point.

V_r: Relative radial velocity

V_θ: Relative angular velocity

α_{ij}: Angle between our vehicle location and the obstacles port or stern vector.

n: Number of discretization points on a candidate path.

ψ_i: vehicle heading

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This is part of ongoing research at the University of Washington Autonomous Flight Systems Laboratory and is only possible as a result of the work of many students before me.

Chapter 1
INTRODUCTION

Unmanned vehicles can serve a wide variety of Intelligence Surveillance and Reconnaissance (ISR) missions. Benefits to emerging markets such a surveying, research, search and rescue, and commercial fishing also exist. It is our goal to advance the current state of USV technology by applying an evolutionary based planning system to a SEAFOX vessel built by Northwind Marine Inc. The path planning system is modified to behave according to the marine rules of the road as defined by the Coast Guard International Regulations for Avoiding Collision as Sea COLREGS [1].

1.1 Autonomous Vehicles in a Primarily Human Environment

In order for the benefits of autonomy to be realized a vehicle must be able to operate independently of constant operator supervision. The use of a USV presents potential risk to the safety of others and loss of property. The level of current USV technology requires constant supervision by operators to ensure avoidance of all obstacles.

One of the more difficult issues related to autonomy is operating in a highly dynamic environment with other vehicles operated by humans. Humans are capable of generating some highly unpredictable behaviors. Therefore, an autonomous vehicle must be flexible enough to deal with unpredictable events or situations and also agile enough to respond quickly to changing conditions. An evolutionary approach to path planning is capable of dealing with these unanticipated events in a dynamic environment.

Obstacle avoidance can be broken into two regimes: near-field or reactive obstacle avoidance and far-field or deliberative obstacle avoidance. This thesis is focused on developing deliberative obstacle avoidance by using Digital Nautical Map (DEM) and RADAR information. A method of avoiding collisions with other vehicles according to the marine rules of the road is described.

The rules of the road are implemented by adapting an evolutionary based path planning system to, when the circumstances dictate, plan paths according to the rules of the road. An evolutionary approach is used because many unpredictable and/or conflicting events can occur in a marine environment. The evolutionary path planner has the ability to balance these different demands and produce a feasible path that is free of collisions with other obstacles. The result is a system which reduces operator workload by autonomously planning paths to meet the demands of a changing environment.

1.2 State of USV Technology

According to a 2003 USV market survey [2], US Navy planners see USVs as an integral part of a more agile naval force. A recent Office of Naval Research (ONR) briefing [3] identified the following benefits,

1. Minimize risk to personnel in high-risk littoral missions.

2. Low cost.

3. Not power limited.

4. Not limited by human factors.

5. Ability to communicate with vehicles both above and below sea.

However, for USVs to be widely accepted technical advances need to be made. One area where we feel we can contribute is to improve USV autonomy. Typically more than one operator is required to run a single USV, one operator to control the USV and one to monitor the payload. In order for USVs to be truly efficient one operator should be able to monitor multiple USVs simultaneously.

The development of USV technology can be dated back to World War II. These first attempts were primarily designed to be torpedo type vehicles to clear mines or obstacles in the surf zone. In 1946 USVs were used to collect water samples after atomic testing on Bikini Atoll. Another common use was (and still is) to use the USVs as target drone boats for target training purposes [4]. These vessels were typically operated as radio controlled boats.

Recently, however, the focus has shifted from a simple radio controlled configuration for target practice, to much more complex ISR missions. Attacks on Marine assets such as USS Cole (2000), French oil Tanker Limburg (2002), Phillippine Superferry 14 (2004), and Khor Al Amaya oil terminal (2004), have driven an increased interest in anti-terrorism and littoral warfare. The Bush Administrations' National Strategy for Maritime Security states that "infrastructure and systems in the marine domain... have increasingly become both targets of and potential conveyances for dangerous and illicit activities." [5]. According to a recent congressional report [6] the threat of maritime terrorism is significant and can take many different forms. The attacks have increased national awareness of maritime security. Increased awareness coupled with advances in technology have led to a natural increase in attention on using USV technology for maritime anti-terrorism efforts.

Typical unmanned vessels today are of the pleasure craft size or smaller. Figure 1.1 shows a couple examples of personal watercraft size USVs. The vehicle shown in the picture on the left is an advanced version of an earlier USV known as the OWL. The vehicle shown is developed for port security and offered by Science Application International Corporation. The Roboski, offered by Robotek Engineering and pictured on the right, was developed to be a low cost, ship deployable target training device.

(a) SAIC Unmanned Harbor Security Vehicle

(b) Roboski

Figure 1.1: Examples of Personal Watercraft Size USVs.

Some more advanced and larger USVs are shown in Figure 1.2. The Protector, developed by the Israeli company Rafael, is shown in Figure 1.2(a). It is currently being used in the field by the Singapore Navy. With it's integrated weapons system it is touted primarily as a means of force protection or advanced patrol. The Space and Naval Warfare Systems Center, San Diego (SSC San Diego) is developing a USV, shown in Figure 1.2(b), based on a Sea-Doo platform that has autonomous Obstacle Avoidance. Their obstacle avoidance segregates obstacles into two regimes, reactive and deliberative. They define reactive obstacle avoidance as actions taken to avoid near field obstacles (<200-300 yards). This regime uses sensors such as stereo vision, monocular vision, Nautical charts and radar images. Deliberative obstacle avoidance is for far field planning and uses nautical charts and Radar [7]. We have modeled our approach to obstacle avoidance similarly. The Spartan Scout Advanced Concept Technology Demonstrator is shown in Figure 1.2(c). It is developed by a team that includes members of the US, Singapore, and France and is aimed at being a flexible USV with integrated sensor and weapons systems. There are two sizes, 7 and 11 meters each of which can operate for approximately 8 hours [8]. Accurate Automation Corporation also advertises a USV with obstacle avoidance capability [9].

(a) Protector

(b) SSC San Diego USV

(c) Spartan

Figure 1.2: Examples of Pleasure Craft Size USVs.

Another method of pursing autonomy in sea surface vehicles is to develop modular systems that will work independent of vehicle platform. There is an abundance of off-the-shelf autopilot products in the marine industry. These products typically offer waypoint guidance with some “dodge” features where the captain has to manually tell the autopilot to temporarily change course. These systems all require constant operator supervision and are not designed for complex mission planning and execution. A more technically advanced solution is offered by Intellitech Microsystems, Inc. [10]. They have developed an obstacle detection and avoidance system they called GODZILA, it uses RADAR and/or sonar information to detect and avoid obstacles. The Canadian firm, International Submarine Engineering Limited, has developed what they call the Tactical Controller Kit. This is a kit that is designed to transform any manned vessel into a USV [11]. They have also developed an air-deployable rescue boat called the SARPAL (Search and Rescue Portable, Air-Launchable), and the SEAL Retriever Personnel Rescue Vehicle.

Many of the above mentioned vessels and on-board technology offer various forms of obstacle avoidance, but none offer a comprehensive solution, within the framework of a path planning mission management system, to avoid obstacles that range from cargo container ships, to leisure boats, to kayakers, to large flotsam. What we propose here is a step in the direction of more complete autonomy to satisfy the needs of a diverse field of customers.

Chapter 2

USV GUIDANCE, NAVIGATION AND CONTROL SYSTEM

The SEAFOX vessel shown in Figure 2.1 is a small, low cost Unmanned Surface Vehicle manufactured by Northwind Marine Inc. The construction is what is commonly referred to as a RIB, Rigid hull Inflatable Boat. It's aluminum hull and inflatable collars result in a very durable boat. It is small and fast, at 16' in length and about 1500 lbs. Similar to many early USVs, SEAFOX was developed to be a high speed Air Gunnery Target Towing Training System. Since then it has been equipped with video and thermal imaging cameras and adapted for use in marine interdiction applications. It is an ideal boat for USV development because of it's portability and relatively low cost.

2.1 *Autonomous Guidance, Navigation and Control System Architecture*

The autonomous guidance, navigation and control system architecture that we have adopted is shown in Figure 2.2. An operator interfaces with the USV through a ground station. The ground station provides environmental feedback to the operator via video images, a digital nautical map and radar data. The vessel's guidance, navigation and control systems are interfaced by inputting waypoints, or tasks and their locations, through the ground station to the path planning software on board the vessel. In addition, the vessel can be operated manually by remote control, or in a waypoint following mode. Information is relayed between a gateway on the boat and the ground station via a two-way radio link. The gateway controls information flow among the vehicle components and between the command center and the vessel. The

Figure 2.1: SEAFOX operated by radio control on Lake Washington, WA.

planning processor will interface with the vessel actuators, and sensors through the gateway. The University of Washington's contribution to this architecture is shown in the Planning Processor box of Figure 2.2. The planning processor has three primary functions,

- ECoPS/Search algorithms
- Obstacle Avoidance algorithms
- Stand-off algorithms

The search algorithms have been developed by Lum [12] at the University of Washington's Autonomous Flight Systems Laboratory (AFSL) [13]. His approach to searching for and locating targets/anomalies is based on an occupancy map. The search domain is discretized into rectangular cells and each cell is assigned a score

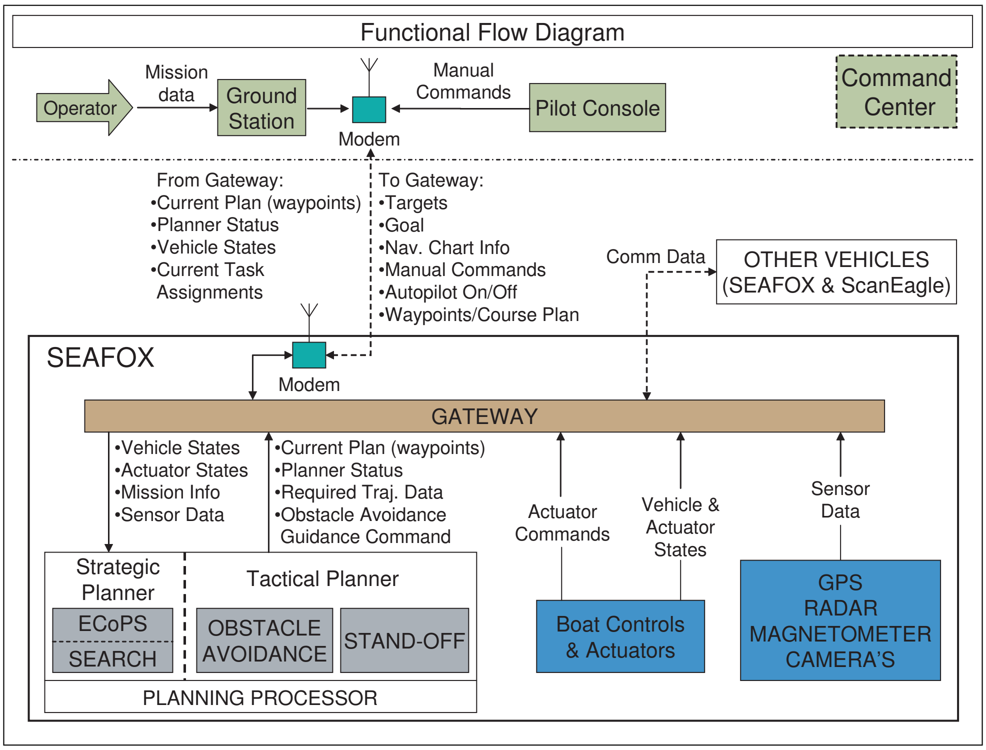


Figure 2.2: Autonomous Guidance, Navigation and Control System Architecture.

based on the probability that the target is in that grid. At each time step, guidance decisions are influenced by the information contained in the occupancy map.

Stand-off algorithms have previously been developed at the AFSL by Rubio et al. [14], and Rysdyk [15]. Stand-off is the ability to stay within a specified distance of a target and monitor it's activity. Once a target is identified and the USV is in close enough proximity, these algorithms will be used to track a target and maintain sensor contact. While the target is being tracked the long range evolutionary planner continually replans the long range path for completing the next mission task. In this manner, when requested, the vehicle can break-off from it's surveillance behavior and immediately return to completing the next mission task without stopping to compute it's path.

This thesis is focused on developing far field obstacle avoidance according to the marine rules of the road as defined by the COLREGS. Concurrently, reactive obstacle avoidance algorithms are being developed by a colleague. The summation of these modules will be a system which is capable of complex mission planning involving search, following/surveillance, and obstacle avoidance with reduced stress/workload on the human operator.

2.2 Evolution-based Cooperative Planning System (ECoPS)

The Evolution-based Cooperative Planning System (ECoPS) is the heart our planning system. The software is designed to plan complex missions autonomously for multiple agents. An agent is any member of the team of unmanned vehicles. The agents involved in the mission are capable of trading tasks through an auctioning process to achieve mission requirements in a constantly changing environment. Tasks and goal location can be changed real time by the operator. For instance a mission may consist of multiple agents collecting intelligence on multiple targets. Once an agent sends back intelligence, through video or some other means, the operator could decide that the agent should follow the target. The agent will then engage the stand-off algorithms and it's tasks are traded autonomously and efficiently with the other remaining agents to complete the mission requirements.

ECoPS is designed such that one operator can operate many unmanned vehicles at a time thus reducing the operator workload. The current state of unmanned technology requires one, and sometimes more, operators to operate one unmanned vehicle. Our software requires only that the operator specify the sites to be visited and the tasks to be completed upon arriving at the site. Once this information is entered the operator is able to focus more on the data acquired and less on the actual guidance of the vehicle.

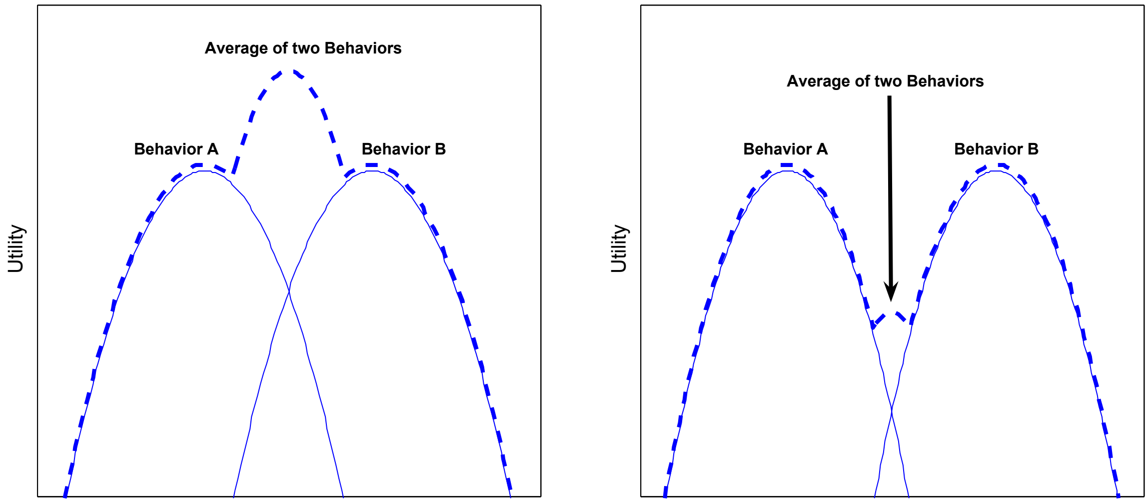
One major assumption is that the vehicle has extensive knowledge of it's surroundings. That is, if the site of interest to visit is mobile, the path planner is capable of dynamically replanning it's path to the site, but only if it can obtain new information about the site's location. If new obstacles appear, or are mobile, the path planner needs to know in order to continually adapt. The path planner provides for inclusion of environmental data and it has been demonstrated to work effectively in a simulation environment.

ECoPS uses a 'world model' to autonomously plan safe and efficient paths. The 'world model' represents all that the software knows about it's surrounding environment. Examples include obstacles and tasks to be completed by the USV. In Chapter 3 we describe how RADAR, GPS, and a digital nautical map are included to provide environmental data in a real-time implementation to be tested on the water. The path planning software provides the decision making or logic required to increase the level of autonomy. However, for the path planner to make good decisions it must have accurate information about the surrounding environment. This makes good integration of sensor data an important priority. In the future more sensors such as stereovision, AIS, or Infrared video could be included to further improve the environmental data.

2.2.1 Issues with Strictly Behavior-Based Control

Operating an autonomous vehicle in a marine environment where obstacles can move in any direction presents a challenge to the system designer. Trying to then follow navigation rules that other vehicles may be blatantly ignoring further aggravates the problem. The Coast Guard Collision Regulations, described in Section 4.1 are designed to aid the boat operator in avoiding collision but allow room for interpretation with the intention of allowing the operator to make the decisions on when a rule is pertinent.

There are situations where strictly choosing one behavior or averaging distinct behaviors could result in a lower than desired utility of the selected path, therefore a strictly behavior based approach should be avoided. A strength of the ECoPS software is it's multi-objective nature. It continually searches for the better path and balances conflicting objectives under multiple constraints by evaluating many continuously evolving paths. In Figure 2.3(a), the highest utility is the average of two distinct behaviors. ECoPS' multi-objective approach is capable of finding the path with the higher utility that is the average of two distinct behaviors. It is also capable of choosing the best distinct behavior if the utility is maximized by one behavior or the other as shown in Figure 2.3(b).



(a) Averaging two distinct behaviors results in a higher utility than choosing one behavior.

(b) Averaging two distinct behaviors results in a lower utility than choosing one behavior.

Figure 2.3: Maximizing Utility of Two Distinct Behaviors.

2.2.2 Single Vehicle Path Generation

The following is a brief description about the generation of paths for a single vehicle. For a more detailed description see Rathbun and Capozzi [16].

The path generation process begins by randomly creating a predetermined number of paths. The paths are created by joining straight line and constant radius segments

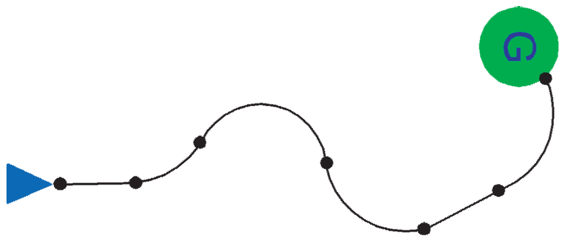


Figure 2.4: Example of a Path connected by constant radius curves and straight line segments.

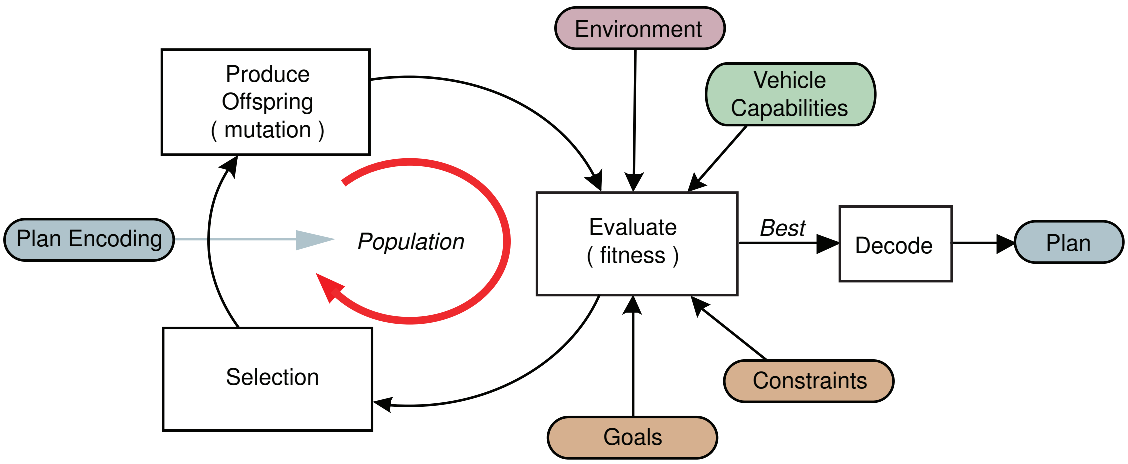


Figure 2.5: Evolutionary Process.

together end to end as shown in Figure 2.4. Once these are created the evolution process can begin. Figure 2.5 shows the evolutionary process. There are three basic steps; Evaluation, Selection, and Offspring Creation (mutation).

The evolution process begins by evaluating the set of randomly generated paths with an objective function. The objective function can vary depending on the mission type but typically would involve things like fuel consumption, survivability, mission accomplished (or not), timely arrival, etc... The general objective function is shown in Eqn. 2.1 [17].

$$J = \sum_{i=1}^{N_T} (R_i(N) - R_i(s_p)) - C(Q(s_p)) \tag{2.1}$$

The first term in Eqn. 2.1 is a function of the environment states and the candidate path, Q. It is the score gained by a candidate path during the time $t_{sp} < t \leq t_N$. The score is increased by accomplishing tasks. R_i is the score for accomplishing task i. The vehicle score at the end of the current trajectory is $R_i(s_p)$. $R_i(N)$ is the score for the path from the end of the current trajectory until it's endpoint. The difference between $R_i(N)$ and $R_i(s_p)$ is the score to be gained by choosing the path. $C(Q(s_p))$ is the cost of the candidate path, Q, from the end of the committed trajectory to the end point of the path. Costs include fuel consumption, attrition and other mission specific parameters. The rules of the road are implemented by adding another term into the cost function, $C(Q(s_p))$. The added term is given by Eqn. 4.8 in Section 4.3.

Once the initial set of paths are created their cost and score is evaluated. The objective function is used to evaluate the individual paths for their "fitness". A higher value means the path has better fitness. As shown in the diagram in Figure 2.5 many parameters are considered when calculating the fitness. Vehicle capabilities, goals, constraints and environmental information are fed to the objective function to evaluate a path score and cost. The paths are then evaluated in a tournament. The ith candidate path competes against the other paths. For each opposing path that the candidate path has a higher objective function result, the candidate path is given a point. The process is repeated n times, where n is the number of paths and all paths get their turn as the candidate path.

Moving clockwise from the evaluate box in Figure 2.5 the next step is selection. At the end of the fitness evaluation the paths with the highest scores are selected to be parents for the next generation of paths. For a more detail explanation of the fitness and selection process see Pongpunwattana [18].

Now that parents have been selected, offspring must be created. These offspring are created by randomly mutating the parent paths that were selected. There are five mutation mechanisms.

1. Mutate 1-Point - This mechanism takes out a segment in the path. There are two sections of path left over. A new segment is randomly appended to the end of the first chunk of path and the second chunk of path is moved and connected to the end of the newly created segment.

2. Mutate 2-Point - This mechanism cuts a chunk out of the middle of a path and then randomly generates segments to reconnect the beginning and end of the path.

3. Crossover - This method takes the beginning of one path and the end of another and then connects them.

4. Mutate Shrink - Removes some random number of segments from the end of a path.

5. Mutate Expand - Adds a random number of segments to the end of a path.

Figure 2.6 shows an example of the *Mutate 1-Point* mutation process. The path on the left, path a, is the initial path. The beginning of the path is at the bottom represented by a grey icon, the end, or goal location, is represented by the green circle with a 'G'. The paths are created by randomly connecting path segments together. This does not ensure that the path connects with a desired goal location. In the path planner there is *Go To Goal* functionality that connects the end of the generated path to the desired goal location. The first step in the mutation process is to remove the *Go To Goal* section of the path, shown in path b. Then in path c, a middle segment has been removed and a new random segment inserted. Also, the chunk of path that had been cut off is connected to the end of the new segment. Finally in path d the *Go*

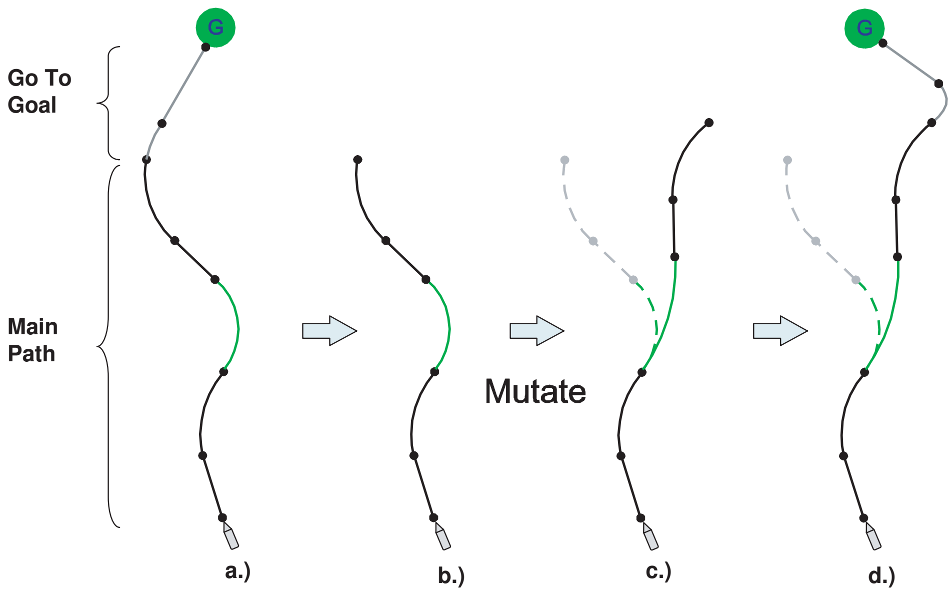


Figure 2.6: Example of Mutate 1-Point Mutation Process.

To Goal segments connect the mutated path back to the goal location. See Rathbun et al.,[19] for a more detailed description of how the paths are mutated, and connected to the goal location.

2.2.3 Dynamic Path Planning

The path planner is capable of dynamically replanning the path as environmental information is changed/updated. Figure 2.7 shows how dynamic planning is handled. The beginning portion of the current best path is committed to the guidance system, this is referred to as the 'committed trajectory'. While the vehicle is navigating the committed trajectory the planner is continuously replanning from the next "spawn point", denoted as the start point in Figure 2.7. The "spawn point" corresponds to the end of the committed trajectory. Once the "spawn point" is reached, the beginning of the current best path according to the evolution process is sent as the

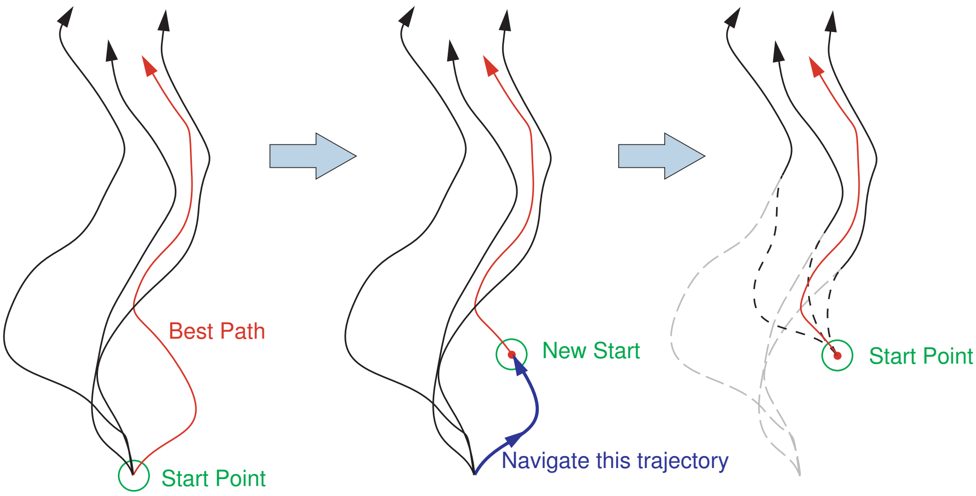


Figure 2.7: Dynamic Path Planning.

new committed trajectory to the guidance system.

2.2.4 Market based protocol

The ECoPS path planner uses a market based protocol developed by Pongpunwattana [18] to decrease operator workload and autonomously complete complex missions. The task trading process has no centralized planner assigning tasks. Rather each vehicle makes it's own trading decisions. The focus of this paper is on one vehicle navigating according to the marine rules of the road but a complete description of the ECoPS path planner must include a mention the task trading ability.

Chapter 3
INTEGRATION OF ENVIRONMENTAL INFORMATION

The ECoPS software is very flexible to changes in environmental information. We seek to use a variety of sensors to gain as much knowledge of the environment as possible. For our initial demonstrations in a controlled environment we have integrated a Digital Elevation Map, GPS, and RADAR data. In the future more sensors will be added to increase the richness of the world state information.

Figure 3.1 shows the information that flows into and out of the path planner. Some of the information such as Team Vehicles, and Team Tasks are implemented by an operator during the initialization of the mission. These may be updated by the operator or ECoPS, if for instance, it has reason to believe a team member is no longer operational. Other information such as environmental and obstacle information must be obtained from other sources. We obtain obstacle information from a RADAR sensor, water depth information from digital nautical charts, and our vehicles location from GPS. The GPS and RADAR data are obtained from sources that use NMEA 0183 protocol. The implementation of this protocol is discussed in Sections 3.4 and 3.5. The depth of water is obtained from a Digital Elevation Map (DEM) and is discussed in Section 3.2.

3.1 Adaptation of ECoPS to USVs

The path planning software was originally developed for use on UAVs. The vehicle dynamics and operating environment are quite different between UAVs and USVs. Therefore ECoPS was modified to work with USVs.

In simulation the vehicle states are updated every time step using a simple update

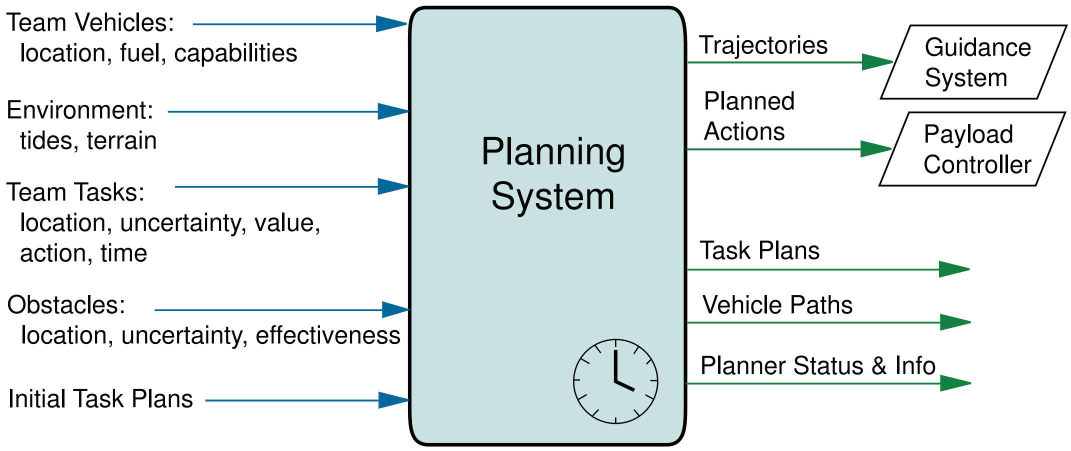


Figure 3.1: Path Planning System Data Flow.

procedure. The vehicle moves with constant velocity in short straight line segments on the path. The desired location at the end of the current time step is calculated. Then the heading is changed to point at the desired location in the path. The command is analogous to a rudder command that would be issued by an autopilot. Because we do not aim to maneuver the vehicle aggressively we ignore vehicle dynamics. Rather, the capabilities of the vehicle, such as minimum turn radius, are coded into the path generation process. As a result we don't worry about exceeding the limits of the vehicle in the state update process. The vehicle position is then updated with,

$$Pos = v\Delta T \tag{3.1}$$

where, v is velocity, and ΔT is the time step.

The environment and the capabilities of a USV are drastically different than a UAV. These differences in environment and capability can be leveraged by the USV to increase the scope of mission scenarios. For instance, a marine vehicle is capable of coming to a complete stop, interacting with hard obstacles, and maintaining a nearly constant position if desired. With a conventional UAV, hard obstacles are carefully avoided and a forward velocity is always maintained. To take full advantage of the USVs capability, environmental data such as depth of water, navigation aids, and moving obstacles must be known. For the purpose of obtaining this information, the integration of sensors using a NMEA 0183 protocol and a digital nautical chart are discussed below.

3.2 Electronic Navigation Charts

A Digital Elevation Map (DEM) of the Puget Sound area was procured from Harvey Greenberg at the University of Washington Department of Earth and Space Sciences. Areas of operation could then be sampled from the DEM and the data formatted for interpretation by ECoPS.

The data is in the Universal Transverse Mercator zone 10 (NAD27) projection. The data forms a grid which has 30m resolution so some important features such as buoys and shallow water boulders do not show up. The Southwest corner of the grid is (518310, 5234460) or (47°15’55”, 122°45’29”) and the Northeast corner is (551220, 5289150) or (47°45’20”, 122°18’59”). We decided to use this section of data because it gives a good variety of land/water features. There are islands, channels, peninsulas, and open water.

This data does not have high enough resolution for real autonomous missions but it is good enough to run simulations and also perform on the water testing. The long term solution is to integrate ECoPS with Digital Navigation Charts from the National Geospatial-Intelligence Agency (NGS). The specification is available for free but it was a significant enough project that the integration is left for a future project.

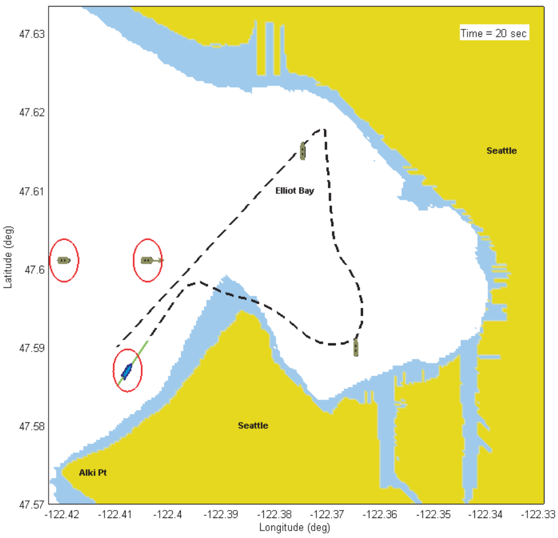
3.3 Simulation Results using a Kinematic Model and Digital Elevation Map

Using the kinematic model and an integrated Digital Elevation map simulations were run which show ECoPS ability to navigate through an environment with moving obstacles. In this case we modeled two ferries coming to dock in downtown Seattle. Their schedules are known and they have AIS transmitters [20] so we assume their locations are known with a high level of certainty. In Figure 3.2(a) the USV is maneuvering into Elliot Bay, WA and a ferry is also traveling into the bay cutting near a point. In Figure 3.2(b) the USV has traveled between the point and the ferry and is approaching the first target to be investigated. Then in Figure 3.2(c) the USV must again avoid the ferry on it's way to investigating the second target. This will be a good application of the Marine Rules of the Road (to be discussed in chapter 4). It is common courtesy to pass behind large vessels due to their low level of maneuverability. Finally in Figure 3.2(d) the USV is returning to it's home location but must avoid a second ferry which is traveling through the direct path back to base. Note, in the figure, the light blue is shallow water and the yellow represents land. The ability to avoid land and moving boat traffic while planning efficient routes to the target locations demonstrates ECoPS ability to handle multiple objectives simultaneously.

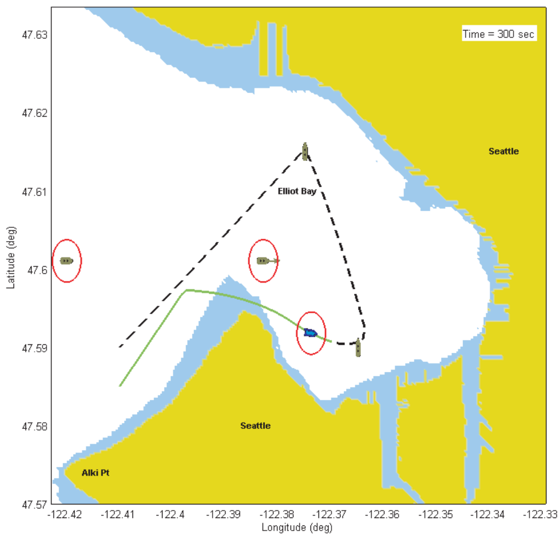
In Figure 3.3 the task is to follow and monitor a vessel in Elliot Bay. At first, in Figure 3.3(a), the target is stationary and the path planner plans an efficient direct route. Then in Figure 3.3(b) the target has begun to move and the path planner is able to adapt its path to the changing position of the target. Our vessel follows the target vessel while avoiding incoming ferry traffic in Figure 3.3(c). Then the target changes direction and our vessel continues to follow while avoiding the second incoming ferry, Figure 3.3(d). Again ECoPS' multi-objective nature is demonstrated, this time in it's ability to follow a moving target and avoid an incoming ferry without hitting the ferry or losing contact with the target.

3.4 Integration of GPS

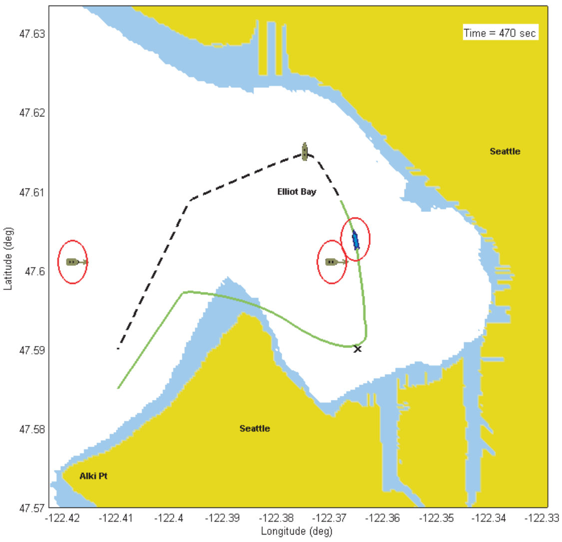
Integration of GPS with ECoPS is critical for feedback of vehicle states. Our particular GPS unit is integrated with a compass and provides position, heading, course over ground, and speed.



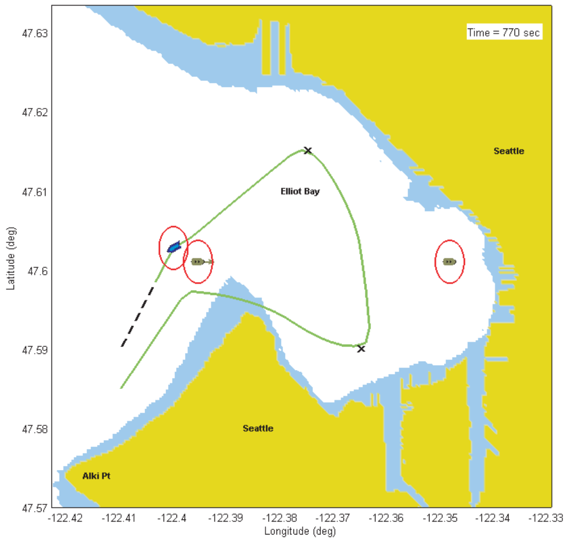
(a) Start of Reconnaissance Mission.



(b) Approach First Target.

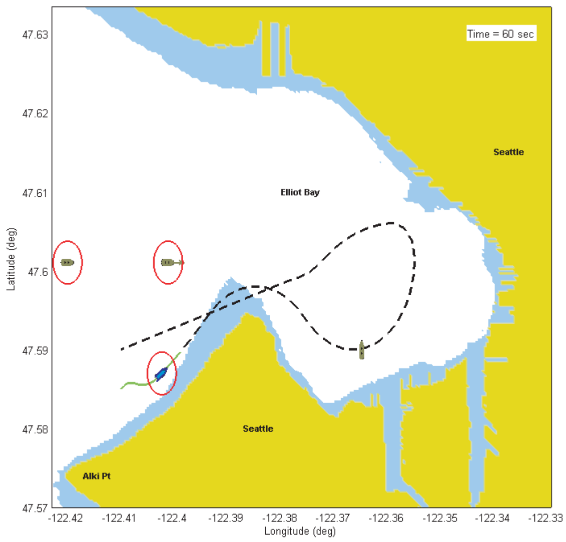


(c) Avoid First Ferry.

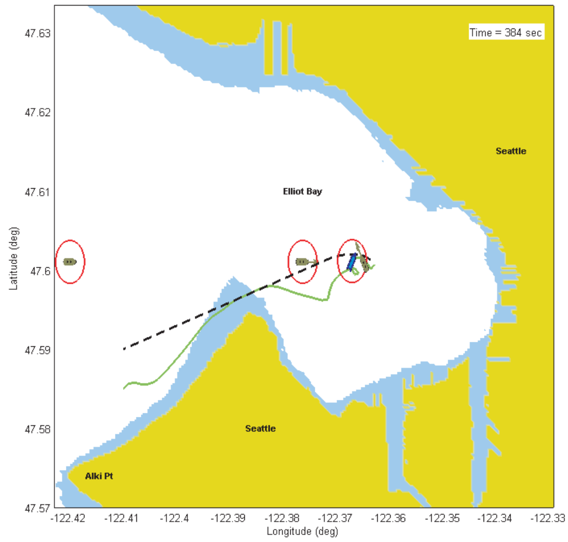


(d) Avoid Second Ferry.

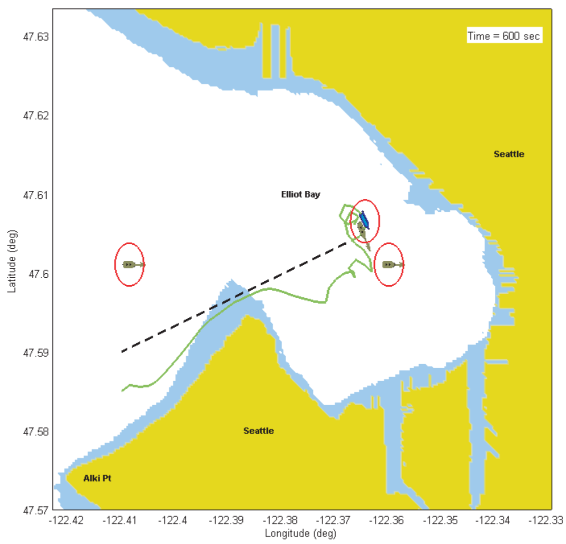
Figure 3.2: Simulation of a reconnaissance mission in Elliot Bay while avoiding scheduled Ferry Traffic. Light blue is shallow water and yellow is land. (Click for Movie)



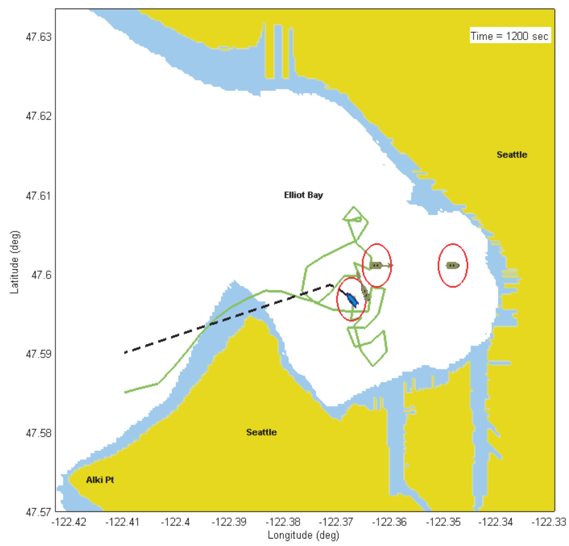
(a) Start of Surveillance Target Mission.



(b) Approach Moving Target.



(c) Avoided First Ferry While Maintaining Contact with Target.



(d) Avoided Second Ferry While Maintaining Contact with Target.

Figure 3.3: Simulation of a surveillance mission in Elliot Bay while avoiding Incoming Ferry Traffic. Light blue is shallow water and yellow is land. (Click for Movie)

The National Marine Electronics Association (NMEA) has specified two communication protocols for marine electronic, NMEA 2000 and NMEA 0183. NMEA 0183 is the predecessor to NMEA 2000 and was developed so that marine electronic components from different manufacturers can communicate with each other protecting consumers against having to use one manufacturer for all the systems on a vessel. NMEA 2000 is a CAN-bus protocol whereas NMEA 0183 is based on ASCII serial communication. Even though NMEA 2000 is newer and has greater capacity NMEA 0183 seems to be the more commonly used communication protocol among consumers. As such we have chosen to use NMEA 0183 devices wherever possible.

The NMEA 0183 standard is copyrighted by the National Marine Electronics Association and at the time of this writing costs $270 [21]. An example of a NMEA 0183 sentence is shown in Figure 3.4. All NMEA 0183 sentences start with a five character identifier preceded by a '*$*'. The '$' indicates the start of a new sentence, '*GP*' indicates that the message is from a GPS device, '*GLL*' says what kind of sentence it is (there are many sentences that a GPS unit could send), in this case the sentence is, "Geographic Position, Latitude and Longitude". The data is deliminated with a comma. The sentence is terminated with an asterisk followed by an optional checksum. The checksum is the 8-bit exclusive OR of all characters in the sentence between the '*$*' and the '*' (including the commas). The result is converted to two ASCII characters (0-9,A-F) and appended to the end of the sentence [22].

3.5 Integration of RADAR data

RADAR data is used to obtain information about obstacles that are not known a priori, primarily other vessels. As with GPS, RADAR data can be obtained from a NMEA 0183 sentence. Typically an Automatic Radar Plotting Aid (ARPA) accessory needs to be purchased to translate the raw radar data into a NMEA sentence. The information available from the radar is:

```
$GPGLL,4735.4027,N,12215.2357,W,224709,V*58

4735.4027    =   Latitude 47° 35.4027′
N            =   North (S = South)
12215.2357   =   Longitude 122° 15.2357′
W            =   West (E = East)
224709       =   Fix time in hhmmss UTC
V            =   Data Invalid (A=Valid)
```

Figure 3.4: Example of a NMEA 0183 Sentence.

1. Target number
2. Target distance from own vessel
3. Bearing from own ship
4. Target speed
5. Target course
6. Distance of closest point of approach
7. Time in minutes to closest point of approach. (-) means moving away
8. Target status L/Q/T (lost from tracking/in process of acquisition/tracking)
9. Time of data in UTC format hhmmss.ss
10. Automatic or manual acquisition

A single NMEA radar sentence contains information on one target and up to ten targets can be tracked at a time. As each sentence arrives in the path planner the data is stored in a vector. The data is identified in the vector by the associated target number.

3.6 Automatic Identification System

The Automatic Identification System provides detailed information on large vessels which can be integrated with obstacle avoidance algorithms to define safe distances to objects and predict future states of large vessels. It's data is also communicated via a NMEA 0183 sentence. The AIS system broadcasts the following useful information every 2-10 seconds while underway and every 3 minutes while at anchor.

1. Rate and direction of turn
2. Speed over ground
3. Position accuracy
4. Longitude
5. Course over ground
6. True heading
7. Time in minutes to closest point of approach. (-) means moving away
8. Time stamp (UTC)

In addition, every 6 minutes an AIS system broadcasts the following information which may be useful for navigation and/or target identification,

1. Radio call sign
2. Name

3. Type of ship/cargo

4. Dimensions of ship

5. Destination

6. Estimated time of arrival at destination (UTC)

Note, the above information is for a class A AIS system. Class B systems are under development and nearly identical to Class A systems. Class B systems are intended for vessels that, by the International Maritime Organization (IMO) carriage requirements, are not necessarily required to carry AIS. The most notable difference between the two systems is that class B does not transmit rate of turn information.

Chapter 4

MARINE RULES OF THE ROAD

The increased use of USVs presents new law and policy issues that have not been addressed. Current law does not specifically address the use of unmanned vehicles in a marine environment. The use of such vehicles presents a risk of injury and property damage. Showalter [23] in looking at the legality of Autonomous Underwater Vehicles found that some semi-submersible vehicles may not be considered "vessels" at all and therefore are not subject to current regulations. The Coast Guard says that the vehicle must be "...engaged in or suitable for, commerce or navigation and as a means of transportation on water" in order to be a vessel. So autonomous vehicles used for scientific purposes that are simply used to study and explore may, in fact, not fit under the current definition of a "vessel". Her study is primarily concerned with submerged and semi-submerged autonomous vehicles. However, it is reasonable to think that the same semantic issues could be argued for USVs.

A natural and prudent solution is for the designer to follow the International Collision Regulations (COLREGS) [1] until more precise law regulating USVs is enacted. In this chapter, integration with the evolutionary path planner, of a method for obeying the marine rules of the road, is discussed.

A graphical interpretation of the rules of the road is shown in Figure 4.1. The focus is on two scenarios, head-on collision and crossing collision. Other scenarios are left to ECoPS's native obstacle avoidance algorithms. The definitions of the rules and how we interpret them are in subsequent sections. The angles that define whether we are in a head-on or crossing collision scenario are discussed in Section 4.3.2.

There have been a few previous efforts to apply the Rules of the Road for au-

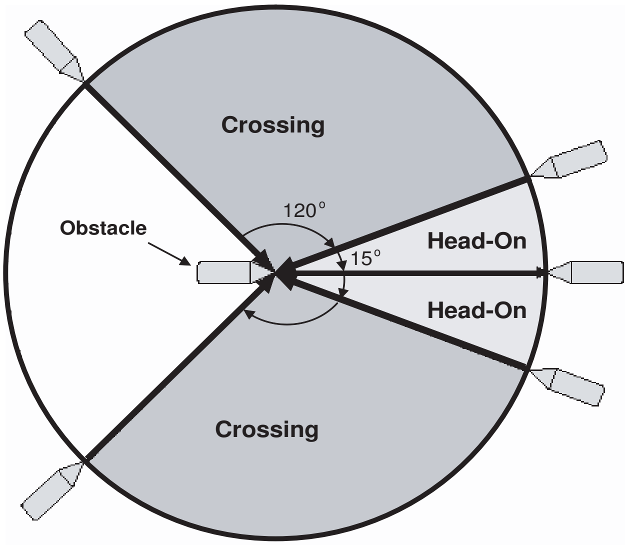


Figure 4.1: Collision Scenario Definition

tonomous collision avoidance. The complexity and uncertainty of modeling marine vehicles and their surrounding environment led Lee et al. [24], to use a fuzzy logic approach to satisfying the COLREGS. Two groups, who have done actual testing on the water, with vehicles of comparable size to our testbed are Benjamin et al. [25] and Larson et al.[7]. In Benjamin et al., they use interval programming based multiobjective optimization to implement a COLREG compliant system. As discussed in section 2.2.1, strictly following a COLREG behavior can lead to less than desirable results because of the complexity of the marine environment. They have chosen to use multiobjective optimization to balance the fact that simply using a behavior based approach can lead to suboptimal results. Larson et al. use a projected obstacle area to develop an estimate of possible future locations of an obstacle. The choice of vehicle action is then discretized into three possible actions based on the vehicles location relative to the obstacle.

4.1 International Regulations for Avoiding Collisions at Sea

A survey of the COLREGS reveals that most of the rules concern lighting, warning signals, application of rules, and definitions etc... and are not of concern for the designer of path planning software. Some specific rules that require our consideration are rule numbers:

7, 8) Rules 7 and 8 discuss identifying a possible collision and the action to take. These are discussed in section 4.2 and 4.3.

9) Rule 9 discusses navigation through a narrow channel and is not discussed here.

14) Rule 14 defines Head-On Collision, see Section 4.1.1

15) Rule 15 defines Crossing Collision, see Section 4.1.2

16-18) Rules 16-18 determine the hierarchy of the right-of-way. It is our assumption that our vessel will never have the right-of-way and will always be the vessel to take action to avoid the others.

4.1.1 Head-On Collision Definition

Rule 14 states the conditions for a head-on situation,

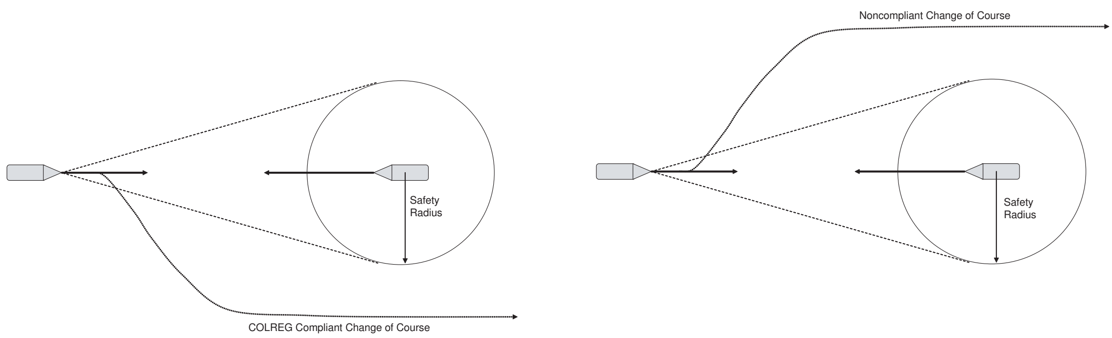
"(a) When two power-driven vessels are meeting on reciprocal or nearly reciprocal courses so as to involve risk of collision each shall alter her course to starboard so that each shall pass on the port side of the other.

(b) Such a situation shall be deemed to exist when a vessel sees the other ahead or nearly ahead and by night she could see the masthead lights of the other in a line or nearly in a line and/or both sidelights and by day she observes the corresponding aspect of the other vessel."

A pictorial interpretation of the rule is shown in Figure 4.2. The rule is written in such a way as to be interpreted by a human operator. This poses some issues with trying to translate the rule to an autonomous vehicle that typically requires a more precise definition. It was decided to use the rule shown in Eqn. 4.1. $\Delta\theta$ is shown in Eqn. 4.2 and ψ_1 and ψ_2 are our vehicles heading and the obstacles heading respectively. When the condition is true we will consider our vessel to be in a head-on configuration with another moving obstacle.

$$|180 - \Delta\theta| \leq 15^\circ \tag{4.1}$$

$$\Delta\theta = \psi_1 - \psi_2 \tag{4.2}$$



(a) Complies with COLREGS. (b) Does not Comply with COLREGS.

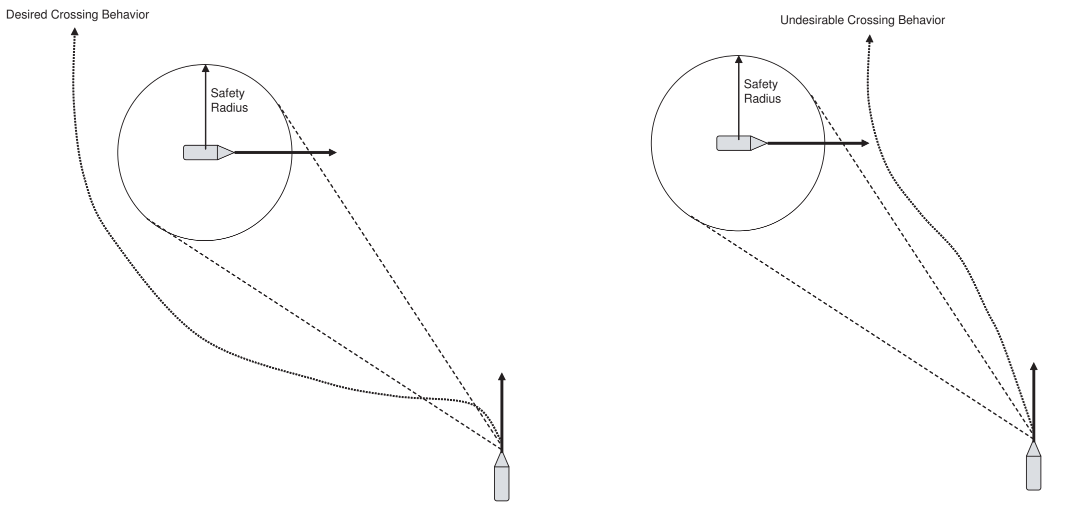
Figure 4.2: Example of Head-On Passing Behavior.

4.1.2 Crossing Collision Definition

Rule 15 pertains to a crossing situation. It states, *"When two power-driven vessels are crossing so as to involve risk of collision, the vessel which has the other on her own starboard side shall keep out of the way and shall, if the circumstances of the case admit, avoid crossing ahead of the other vessel."*

This rule, as with rule 14, involves considerable interpretation by the vessel operator. The rule has been interpreted as the relation shown in Eqn. 4.3, where $\Delta\theta$ is the same as in the head-on scenario. When the condition is true we are in a crossing situation.

$$45^\circ \leq |\Delta\theta| < 165^\circ \tag{4.3}$$



(a) Desired Crossing Behavior. (b) Undesired Crossing Behavior.

Figure 4.3: Example of Crossing Behavior.

An important deviation from the rule as strictly stated is that we will assume that our vessel will always pass behind the other vessel. Consider the case of our autonomous vehicle intersecting at 90° with a ferry or container ship. In this situation it is much less efficient and much more dangerous for the large vessel to change it's course versus our smaller highly mobile vessel. With the addition of AIS data perhaps we could differentiate better between types of boat traffic but even with this added information one could imagine scenarios where it's best if we just pass behind.

4.2 Determination of Possible Collision

Deciding when to take action to follow the Rules of the Road can be difficult for an autonomous vehicle. There is no set criteria for determining precisely when a situation exists. As in rules 14 and 15, the determination is left to the good judgment of the captain. The COLREGS have the following to say about determining if a risk of collision exists:

"Every vessel shall use all available means appropriate to the prevailing circumstances and conditions to determine if risk of collision exists. If there is any doubt such risk shall be deemed to exist." - rule 7

To translate this to a more specific definition we implemented a *Collision Cone* approach detailed in Chakravarthy and Ghose [26]. Their approach is inspired by the idea that collision avoidance and achievement are basically two parts of the same problem. That is, if you can accurately collide with something on purpose, you ought to be able to avoid the object using related principles. At the time of publication of their paper, robotic obstacle avoidance was a fairly new field whereas collision achievement was a fairly mature theory in the aerospace guidance literature. Using the ideas from aerospace literature related to collision achievement they came up the idea of a *Collision Cone.*

The *Collision Cone* is used to predict a collision between a moving point and a moving circle. Figure 4.4 shows the geometry of a collision between a point and a circle. It is shown in [26], that "if a point and a circle of radius R are moving with constant velocities such that they satisfy Eqn. 4.4 at any given instant in time,

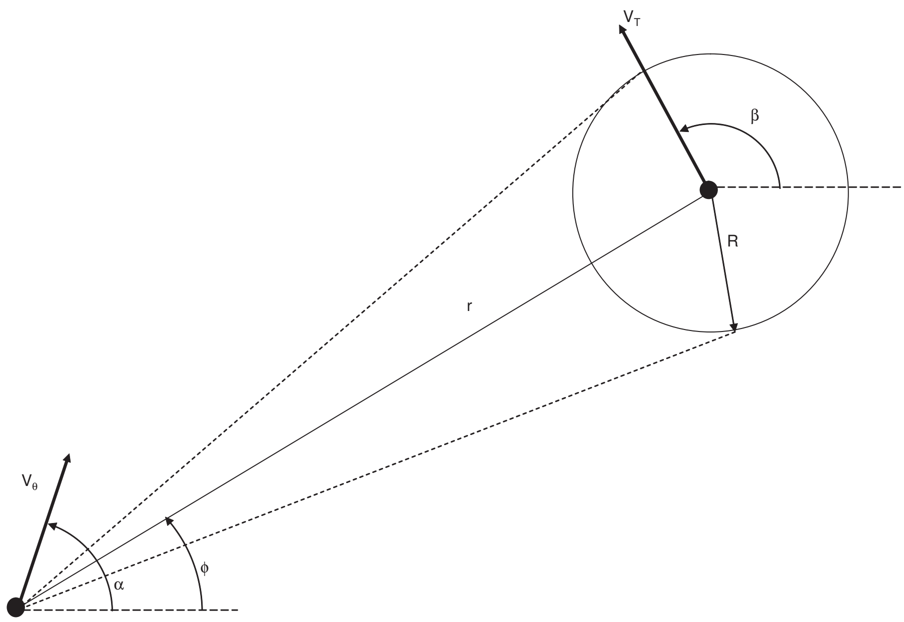


Figure 4.4: Collision Cone Geometry.

then they will continue to satisfy Eqn. 4.4 for all future time." This is also known colloquially as 'on a collision course' if the relative bearing between two vessels does not change.

$$r^2 V_\theta^2 \leq R^2 (V_r^2 + V_\theta^2) \tag{4.4}$$

R is the radius of the circle, r is the distance between the point and the center of the circle, V_r and V_θ are the relative velocity components along and perpendicular to the line connecting the two objects. There are two cases that are of interest when trying to predict collision,

1. Case 1: $V_\theta = 0$ and $V_r < 0$. In this case the objects are on a straight line collision course with each other.

2. Case 2: $V_\theta \neq 0$ and $V_r < 0$. In this case a collision is possible but conditions must be found which result in a collision course.

Using the two cases above, Chakravarthy and Ghose [26], show that when Eqn. 4.5 and Eqn. 4.6 are both satisfied they are necessary and sufficient initial conditions for a collision to occur.

$$r_0^2 V_{\theta 0}^2 \leq R^2(V_{r0}^2 + V_{\theta 0}^2) \tag{4.5}$$

$$V_{r0} < 0 \tag{4.6}$$

Where r_0 is the initial distance between the point and center of the circle, V_{r0} and $V_{\theta 0}$ are the initial relative velocity components along and perpendicular to the line connecting the two objects.

4.2.1 Integration of Collision Cone with ECoPS

The *Collision Cone* is implemented by continuously checking conditions 4.5 and 4.6, relative to an obstacle, for a sequence of seven points. The seven points are illustrated in Figure 4.5. They are,

1. Current obstacle and own vehicle location.

2. Expected obstacle and own vehicle location at next spawn point.

3-7. Discretize the beginning of the base path 5 times and calculate the collision cone at each discretization point. The length of the beginning of the path to be discretized is equal to the length of the next committed trajectory. The obstacles expected state at each point is used for the calculation.

The first time is based on current conditions. The second time is based on the spawn time. The spawn location is the point at which our vehicle will commit to a new trajectory. The third through seventh times are based on the beginning of the base path. The base path is the current best path in the evolver. This is the path that would be committed if the spawn time occurred right now. The length of the base path to discretize is set to be equal to the length of what would be the committed trajectory. The base path is continuously improved as the path planner evolves and generates new mutated paths. If any one of the seven locations results in a condition that is in the collision cone, the fitness evaluator uses the navigation rule cost (rules of the road) to evaluate the candidate paths. If all points are not in the cone, then the navigation rule score is not calculated (i.e. the fitness evaluator does not consider the rules of the road when evaluating candidate paths).

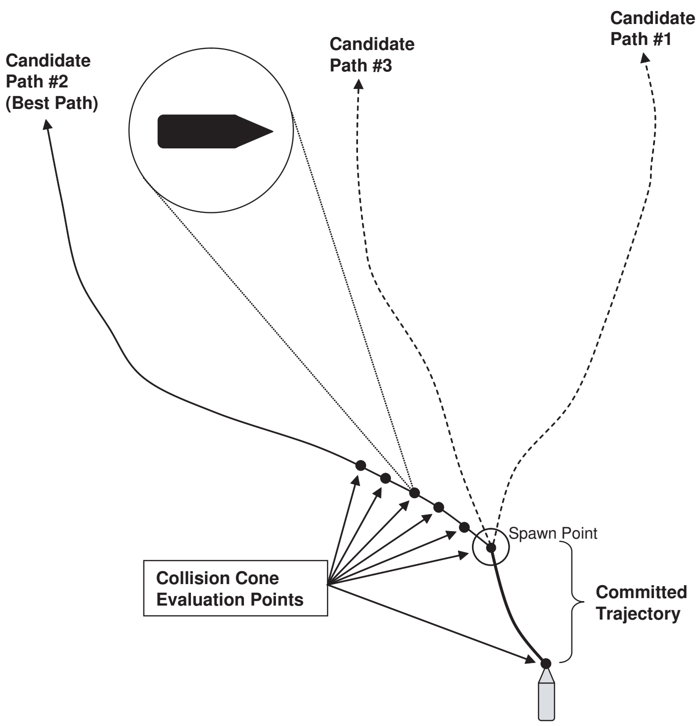


Figure 4.5: Example of Collision Cone Evaluation Points.

For the purpose of calculating the collision cone, all obstacles are modeled as a circle. The circle radius, R, is assigned to obstacles to indicate a cushion for which we don't want our vessel to intersect. This, safety radius, is adjusted based on speed and the type of obstacle. For instance, if our vessel was traveling at 20 knots toward an obstacle that was transmitting AIS data we would know to keep a larger cushion than if going 10 knots toward just a radar return with no accompanying AIS data. Also adjusted based on speed is the "*Rule Range*". The *Rule Range* is the maximum distance to an obstacle for which the collision cone will be calculated. This prevents unnecessary calculations involving far off vehicles.

4.2.2 Identifying the Obstacle

The path planner has it's own native obstacle avoidance and naturally balances conflicting desires to come up with a feasible solution. As such the navigation rules are only applied to the closest vehicle within $\pm 60°$ of our vehicles heading. Figure 4.6 shows the determination of the active obstacle. The vehicle which is closest to our vehicle within a semicircle of radius, *Rule Range*, is the vehicle for which the navigation rules are applied.

4.3 Evaluation of Potential Paths to Avoid a Collision

Once it is determined that our vehicle is on a collision course with another object the vehicle must take action. Again, the COLREGS are open to operator interpretation. They state,

"Any action taken to avoid collision shall, if the circumstances of the case admit, be positive, made in ample time and with due regard to the observance of good seamanship" - rule 8a

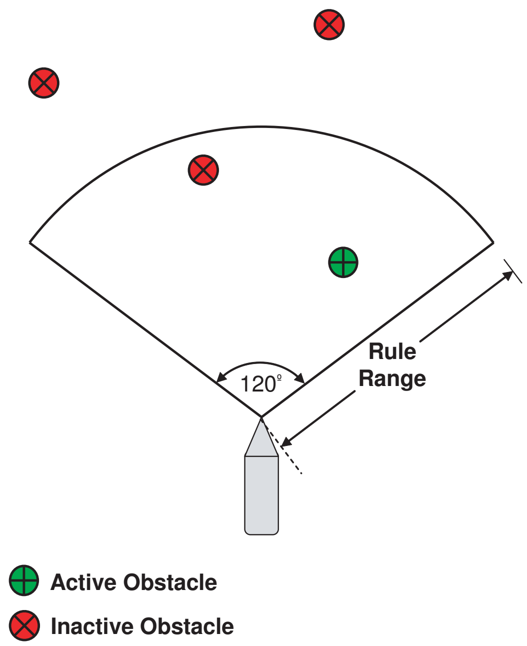


Figure 4.6: Active Obstacle Determination for Collision Cone Calculation.

"Any alteration of course and/or speed to avoid collision shall, if the circumstances of the case admit, be large enough to be readily apparent to another vessel observing visually or by radar; a succession of small alterations of course and/or speed should be avoided" - rule 8b

These rules mean the paths that are generated by ECoPS (Section 2.2) must be evaluated based on the rules described in Section 4.1 and also the degree to which they take "substantial action to avoid collision". This requirement is fulfilled by selecting an appropriate safety radius and *Rule Range*.

4.3.1 Candidate Path Evaluation Process

Figure 4.7 shows a high level view of how candidate paths are evaluated. Once our vehicle is determined to be in the *Collision Cone* of an object, the situation is evaluated to determine which rule must be followed. Once the rule to be used is determined, a flag is set to indicate to the fitness evaluator which rule to use. Concurrently, the length of time between committing to trajectories is reduced by half. The candidate paths that have been generated by ECoPS are then discretized in one second intervals. The number of intervals to use from the beginning of the path, for calculation of the rule cost, is based on our vehicles velocity and is found according to Eqn. 4.7. The length of discretization ought to somehow be related to the relative speed and distance of the two vehicles. This prevents the cost function

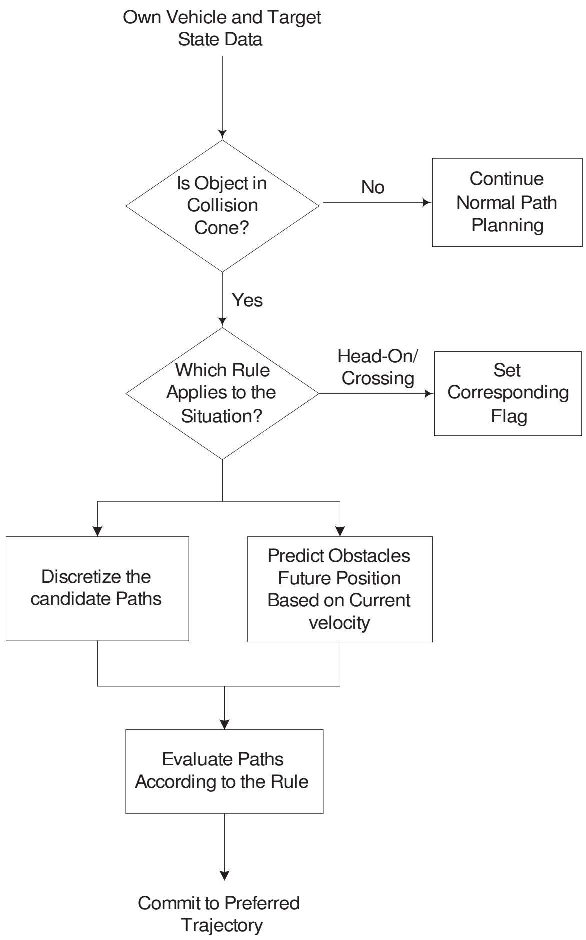


Figure 4.7: Process for Evaluating Candidate Plans.

from evaluating sections of the path that are far on the "other side of" the obstacle. Rather than using relative radial velocity which could significantly change along a committed trajectory as the orientation of the vehicles changes, we chose to base it on our own speed. This has been shown to work well in simulation.

$$NumberOfDiscretizeSteps = 2 * \frac{RangeToTarget}{OwnVelocity} \tag{4.7}$$

Finally, the path is evaluated using the appropriate navigation rule. The future state of the site is predicted by assuming it maintains constant heading and speed. It's position is then projected forward in time in one second intervals. At each predicted future time step our vehicles position and heading at that time are evaluated relative to the objects position and heading. The values are then averaged and the path with the lowest cost is the best path for following the rules of the road. This doesn't always correspond to the best overall path. Things like running into land are given a higher priority.

4.3.2 Rule Determination

Of all the rules discussed above only rules 14 and 15 need to be specifically calculated for evaluating paths. The determination of which rule to use is made according to the diagram shown in Figure 4.1. The diagram is a graphical interpretation of Eqns. 4.1 and 4.3. If the difference between 180° and the relative heading of our vehicle and the obstacle vehicle is between 15° and 135° the situation is determined to be crossing. If the difference between 180° the relative heading is between 0° and 15° then the situation is a head-on collision. Angles between 180° and 135° are considered to be an overtaking scenario. In an overtaking scenario the COLREGS specify that the vehicle being overtaken should maintain it's course and they do not specify a preferred side for overtaking. ECoPS has algorithms that avoid collision based on the vehicles desire to stay alive. As such we have left it to the base path planning to take care of an overtaking situation. Choosing 135° and 15° as the demarcation point between the two regimes was done somewhat arbitrarily. We chose 135° because the angle had to be significantly more than 90° and less than 180°. 15° was the value used in [25].

4.3.3 Head-On Rule Evaluation

The evaluation of a Head-On collision scenario is shown in Figure 4.8. In this picture there are two candidate trajectories and the obstacle is moving directly at our initial position. The black dots represent the end points of discretization intervals. At the end of each interval, a vector 90° to the obstacle's heading, is created pointing to the port side of the obstacle. This vector is referred to as the *Port Vector* and points to the preferred passing side. The angle between the port vector and the line from our position to the obstacle position is calculated. The angle is denoted as α_{ij} in Figure 4.8, where i is the Candidate Trajectory number and j is the discretization step. The calculation of α is wrapped such that $-180° \leq \alpha_{ij} \leq 180°$.

The additional cost to implement the rules of the rules of the road in $C(Q(S_p))$, from Eqn. 2.1, is determined according to Eqn. 4.8. Where n is the number of discretation points on the candidate path as determined by Eqn. 4.7. And q_{ij} is defined by Eqn. 4.9. A path with a lower cost is considered to comply better with the Rules of the Road.

$$C(Q(S_p)) = \sqrt{\frac{\sum_{j=1}^{n} q_{ij}}{n}} \tag{4.8}$$

where,

$$q_{ij} = \begin{cases} 0 & \text{if } \alpha_{ij} < \pm 90°, \\ 1 & \text{if } \alpha_{ij} > \pm 90°. \end{cases} \tag{4.9}$$

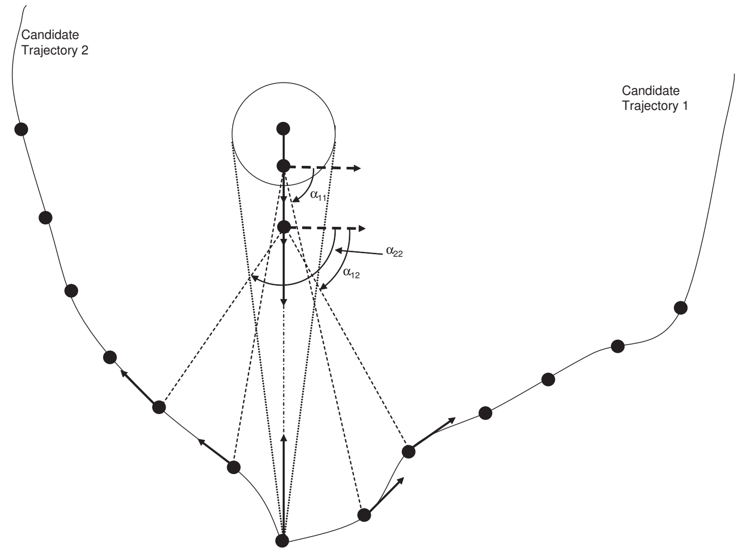


Figure 4.8: Evaluation of Head-On Collision Scenario.

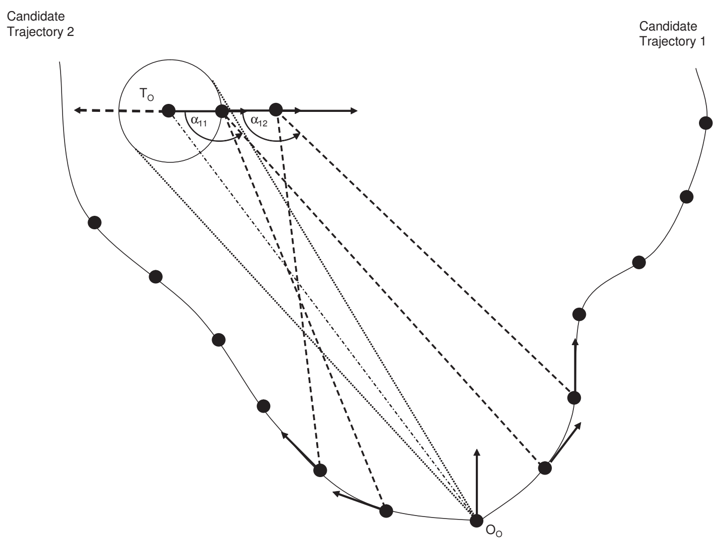


Figure 4.9: Evaluation of Crossing Collision Scenario.

4.3.4 Crossing Rule Evaluation

Evaluation of a crossing situation is done similar to the head-on situation. A picture of this scenario is shown in Figure 4.9. This time a *Stern Vector* is created. This vector points 180° from the obstacles heading and again represents the preferred passing direction. In the figure the dotted arrow represents the obstacles heading rotated by 180°.

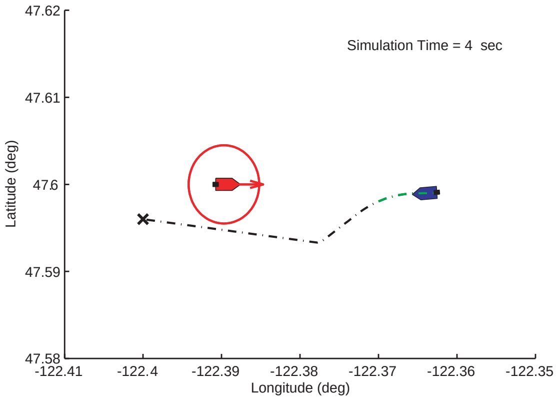
For both head-on and crossing scenarios we have created a vector that points to the preferred passing side. The convienence of this design is that we can use the same cost function for both scenarios. The only difference is in creating the passing side vector. Therefore, Eqn. 4.8 and 4.9 are again used to calculate the cost of a potential trajectory in the crossing collision scenario.

Chapter 5
SIMULATION RESULTS

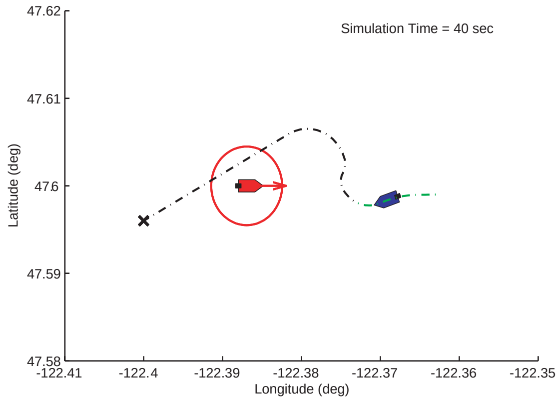
Simulations were run which demonstrate the effective implementation of the rules of the road with ECoPS. First simple simulations without terrain data were run. In the simulations the vehicle states are initialized to encourage ECoPS to plan initial paths that are not COLREG compliant. The paths are then evolved to comply with the COLREGS. Both head-on and crossing scenarios are presented without terrain data. Finally, a simulation using the digital elevation map database for Elliot Bay, WA is shown. In this scenario there are three large vessels navigating in the Bay. Our vessel must avoid these obstacles in a COLREG compliant manner while visiting two targets. The results of these simulations are presented as time sequenced screen captures from movies that were generated using data output from ECoPS.

5.1 Simulation Results without Terrain Data

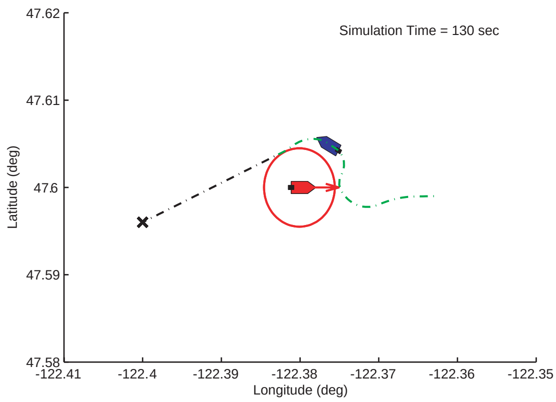
Figure 5.1 shows the results of a head-on collision scenario. The obstacle is the red icon with the arrow pointing to the right with a circle around it. The circle represents the safety radius which we do not want our vehicle to enter, in this case the radius is 500 meters. The 'x' marks the goal location. The planned path is the black dashed line and the committed trajectory is the green dashed line. In Figure 5.1(a) the initial plan is to pass with starboard sides facing each other. To comply with the COLREGS we must make a maneuver to our starboard such that our ports are facing each other. At simulation time step 40 sec, Figure 5.4(b), the planned path evolves to pass on the port side. The remaining two figures show that we indeed make it safely past the oncoming obstacle.



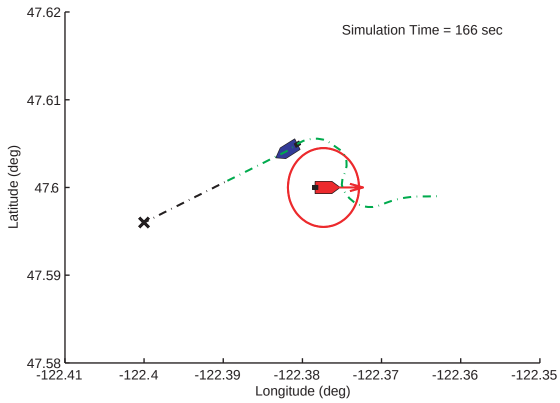
(a) Initial Plan is to Pass on the Starboard Side of the Obstacle.



(b) Planned Path Evolves from a Starboard Passing to a Port Passing.



(c) On the Port Side of the Obstacle.

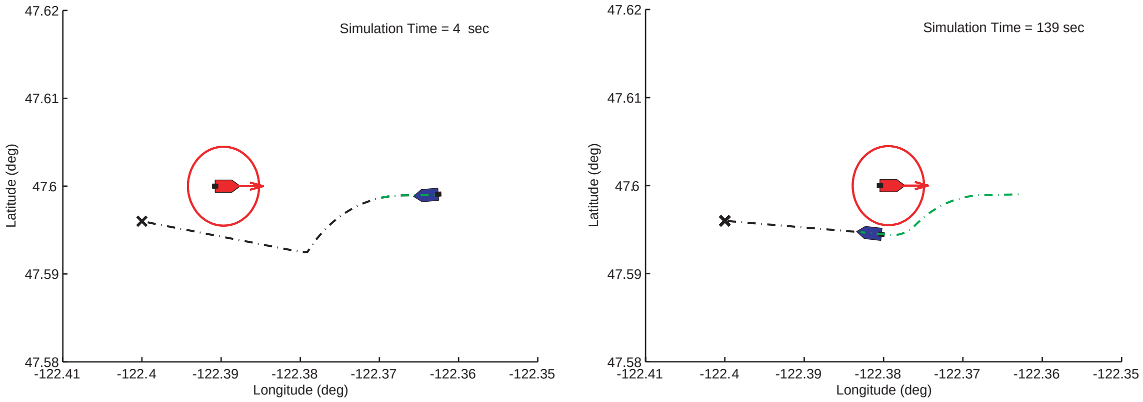


(d) Safely Past the Obstacle.

Figure 5.1: Simulation of a Head-On Collision Scenario using the Rules of the Road. (Click for Movie)

Conversely, Figure 5.2 shows typical results using ECoPS without the *Collision Cone* and rules of the road approach. In this case our vehicle maintains it's original plan and passes with starboard sides facing each other. This behavior would be unexpected by the operator of the other vessel and is undesired.

Figure 5.3 shows the results of a crossing situation using the *Collision Cone* and rules of the road. In this case, because the obstacle is not within the *Rule Range*



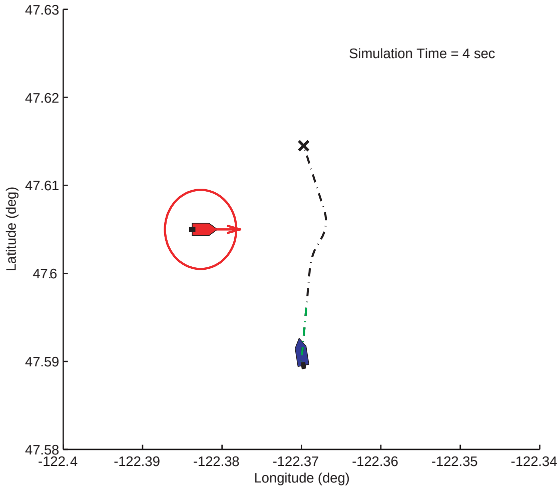
(a) Initial Plan is to Pass on the Starboard Side of the Obstacle.

(b) Planned Path Continues on the Starboard Side of the Obstacle.

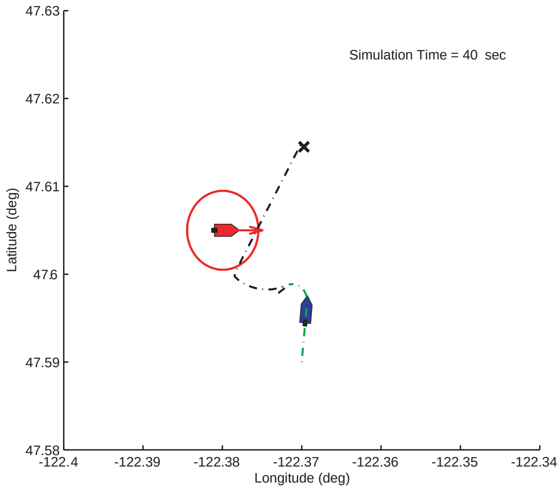
Figure 5.2: Typical ECoPS Results without Collision Cone for a Head-On Situation. (Click for Movie)

and therefore not evaluated in terms of navigation rules in the fitness evaluation, the initial plan, as before, is a path that is not our desired behavior. Once the vehicle enters the *Rule Range*, the planned path is altered to go to the stern of the crossing vehicle, Figure 5.3(b). In this figure it may appear that the new planned path is going to intersect just in front of the obstacle. But the obstacle is moving across the frame and the segment of the path that is in front of the obstacle will not be reached until a significant time in the future. ECoPS predicts where the obstacle will be based on it's current speed and heading. By the time this segment of the path is reached the obstacle has passed through this area. The last two figures show that our vehicle is able to safely pass behind the oncoming obstacle.

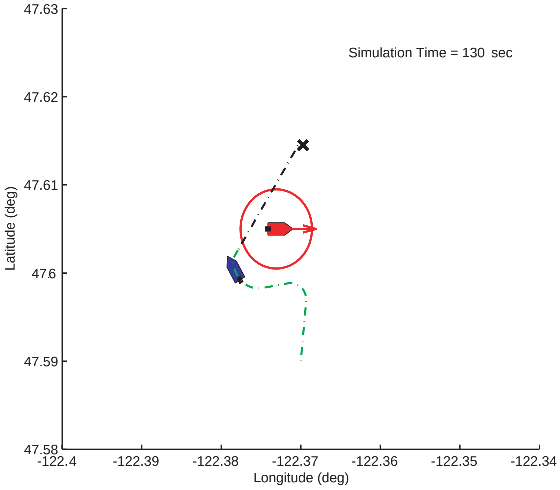
Again, without the collision cone, Figure 5.4, we can see that our vehicle maintains it's initial path, in this case crossing the bow of the obstacle. This could be unexpected if the vessel we are crossing is large like a ferry. Because we do not have high confidence information about the size or type of the obstacle, we have made the decision to always call this undesired behavior and pass behind other vessels.



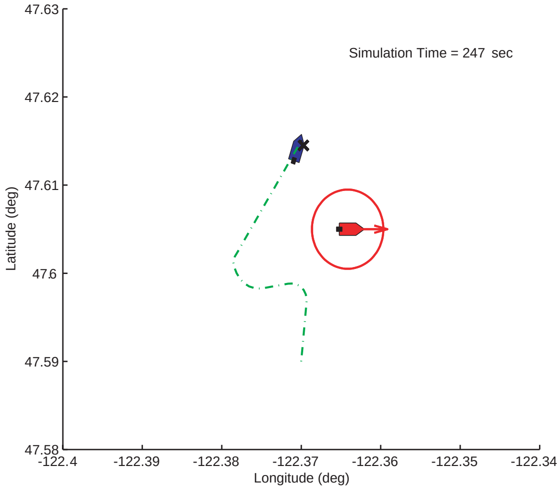
(a) Initial Plan is to Pass Across the Bow.



(b) Planned Path Switches to Pass to the Stern.

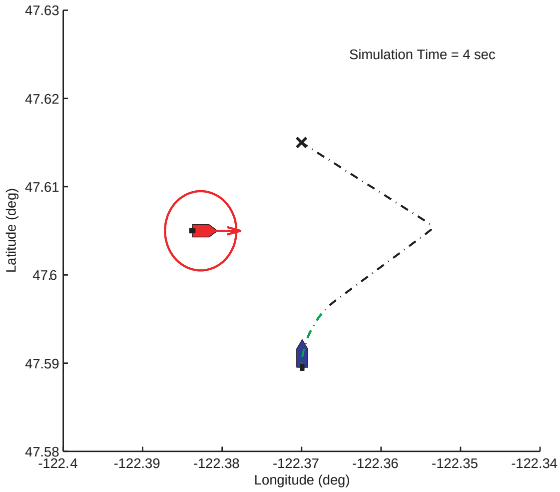


(c) At the Stern of the Obstacle.

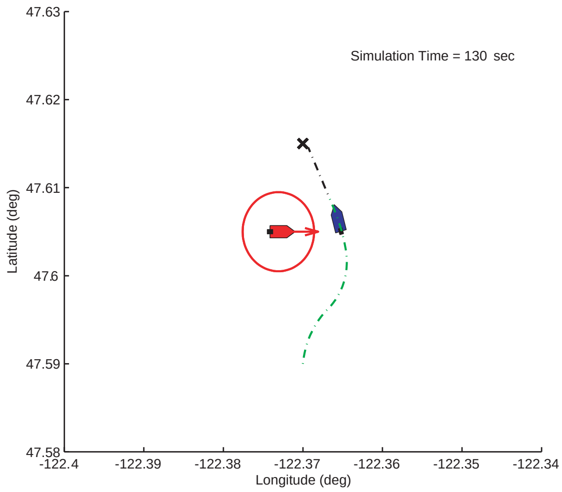


(d) Safely Past the Obstacle.

Figure 5.3: Simulation of a Head-on Collision Scenario using the Rules of the Road. (Click for Movie)



(a) Initial Plan is to Pass across the Bow.



(b) Planned Path Continues Across the Bow.

Figure 5.4: Typical ECoPS Results without Collision Cone for a Crossing Situation. (Click for Movie)

5.2 *Elliot Bay Simulation Using Rules of the Road*

Finally, we included the Digital Elevation Map database of Elliot Bay, WA. A simulation is run with our vehicle in a scenario that includes both potential head-on and crossing situations. The scenario involves our vehicle visiting two targets, one on the north side of the bay and one on the south side. It is contrived to force our vessel into potential collisions.

In this simulation we have multiple large vessels traveling throughout the bay. The obstacles could be cargo container ships, ferries, or some other large vessel. The safety radius around each obstacle was set to indicate that the obstacles are large. The targets to be visited are placed in positions so that ECoPS must balance the objectives of avoiding obstacles in a COLREG compliant manner while planning efficient routes to the target and avoiding land.

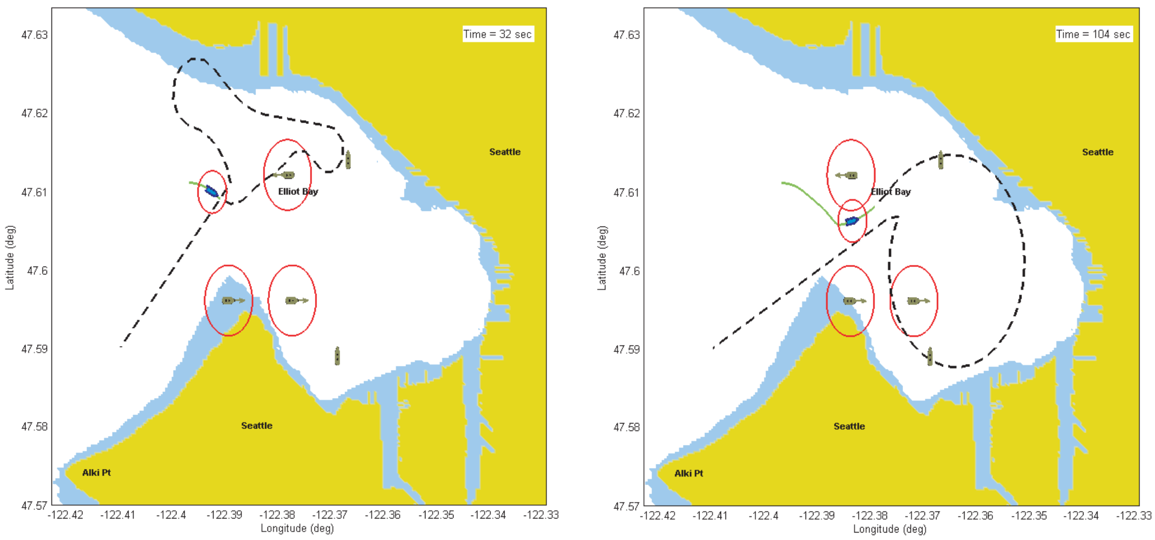
In the following figures, the obstacles are the brown icons with red circles around them, the red circles represent a safety radius of 500m. The targets are the stationary brown icons without red circles. Our vessel is the blue vessel with a smaller red circle. When the target is within the red circle of radius 300m around our vehicle, we will consider the task completed. The planned path is the black dashed line and the committed trajectory is the solid green line.

In Figures 5.5(a) and 5.5(b) our vessel is entering Elliot Bay from the west and has to deal with a head-on collision scenario. The path planner originally plans a path with starboard sides facing. Once it is determined to be on a head-on collision course with the obstacle the planned path evolves so that the vehicles pass with their ports facing each other. Note, the initial planned path is inefficient and does not include completion of all the tasks. The evolutionary technique is nice because it does not require that the optimal solution is found prior to commencing a mission. As our vessel progresses the path is continuously improved by the mutation and selection process. When we look at the final path as shown in Figure 5.7(b) it can be seen that the final path was efficient, completed all required tasks, and avoided other boat traffic in compliance with the COLREGS.

After visiting the first target our vessel turns south to accomplish the second task. As shown in Figures 5.6(a) and 5.6(b), it is faced with a potential crossing collision with two vehicles that are traveling into the bay. At first the plan is to go across the bow of the two vessels, then as the evolution progresses using the rules of the road and the collision cone, the path is evolved to pass at the stern of the crossing vessels.

Finally, in Figure 5.7(a) and 5.7(b) both targets have been visited and now our vessel must avoid a point that sticks out between our current location and our goal location. The goal location is successfully reached

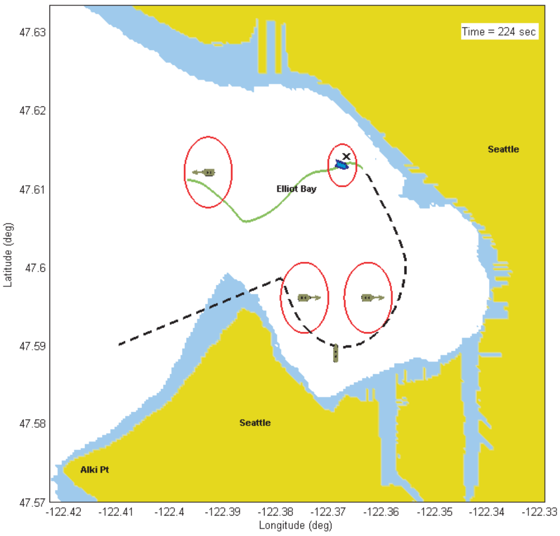
In this simulation ECoPS multi-objective nature was demonstrated in it's ability to plan efficient paths to accomplish multiple tasks while avoiding multiple obstacles and land.



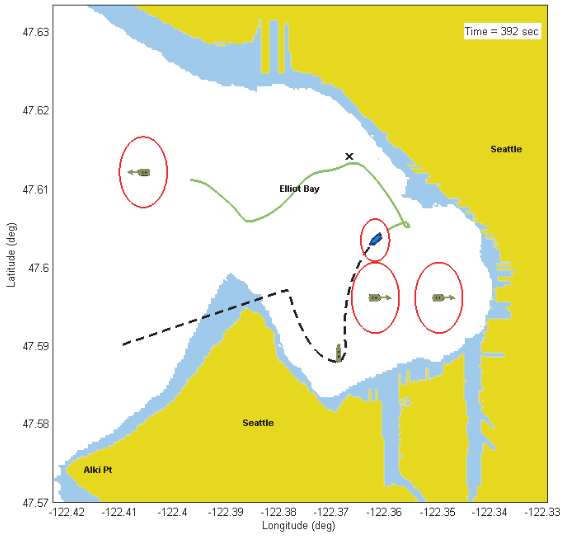
(a) Initial Plan Goes to the left of an Oncoming Vessel.

(b) Plan Changes to Pass with Port Side Facing Oncoming Vessel.

Figure 5.5: Head-On Collision Situation in Simulation that Includes DEM. (Click for Movie)

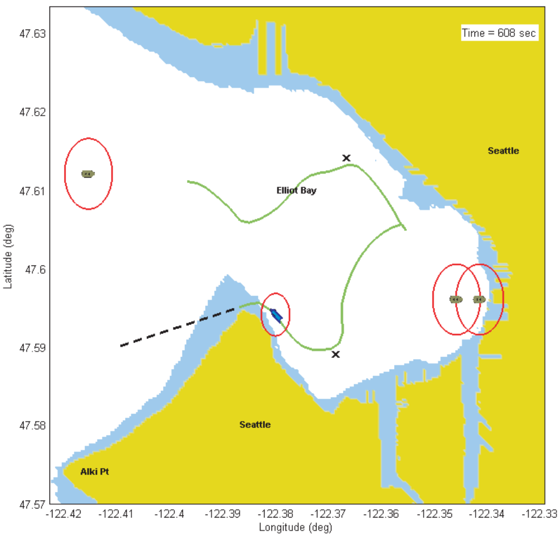


(a) Initial Plan is to go In Front of the Crossing Vessels.

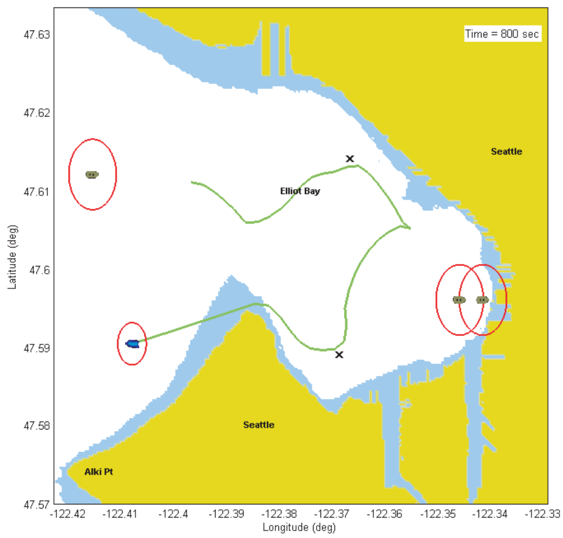


(b) Plan changes to cross behind the crossing vessels.

Figure 5.6: Crossing Collision Situation in Simulation that Includes DEM. (Click for Movie)



(a) Plan Must Avoid Point To Get To Goal.



(b) Successfully Made it to the Goal Location.

Figure 5.7: Avoiding Land on the way to the Goal Location in Simulation that Includes DEM. (Click for Movie)

Chapter 6

CONCLUSION

In recent years the science of Unmanned Aerial Vehicles (UAVs) has reached a high level of technical maturity. Meanwhile Unmanned Surface Vehicles (USVs) have lagged behind in technical development. The need for an improvement in USV technology to a level comparable with their airborne counterparts is clear. With recent attacks on US marine assets and the increased use of IEDs a technically mature USV can be used to reduce the risk to US marine assets and personnel. In addition, benefits to research, surveying, border patrol, marine mammal monitoring, and many other potential customers can also be realized.

Reducing the operator to USV ratio, requires an increase in the autonomous decision making capability of USVs. In order for USVs to be accepted by the public it must be guaranteed that the safety of people and personal property on the water is not compromised by the addition of USVs into the field. A major hurdle to increased autonomy is developing reliable obstacle avoidance algorithms. Obstacle avoidance was broken down into two regimes: reactive or near-field and deliberative or far-field.

In order to achieve satisfactory performance in the face of changing and/or conflicting demands an evolutionary path planning approach was used to address deliberative obstacle avoidance. Presented here was the adaption of the evolutionary path planner to comply with the marine rules of the road as defined by the Coast Guard Collision Regulations (COLREGS).

This effort, coupled with previous technology developed at the AFSL and reactive obstacle avoidance algorithms being developed by a colleague, will result in a system which reduces operator workload by improving the autonomy of mission planning and obstacle avoidance.

A small rugged Rigged Hull Inflatable boat built by Northwind Marine Inc., will serve as the testbed for testing and verification of the obstacle avoidance algorithms. The integration of GPS, RADAR, and Digital Elevation Map data was discussed. This data will facilitate on the water testing testing and verification of the algorithms to be completed in late 2007.

Chapter 7
FUTURE WORK

To further validate the algorithms developed here, real radar data will be used to run simulations. Then in late 2007 field testing is planned for the path planning system. The current digital nautical chart information is in a 30m grid, in the future the path planner will be integrated with digital charts from the National Geospatial-Intelligence Agency (NGS). This will improve the fidelity of environmental knowledge by including hard obstacles such as, navigation buoys, which need to be avoided. Also, inclusion of AIS will give us more knowledge about larger vessels and stereovision will improve the near-field obstacle avoidance.

7.0.1 Heterogenous Teams

The Autonomous Flight Systems Lab (AFSL) at the University of Washington [13] has many years of experience in the field of UAVs and wants to expand that expertise to include USVs with the eventual goal of cooperative mission planning by groups of heterogenous teams including UAVs, USVs, and Unmanned Underwater Vehicles (UUVs).

There are practically an infinite type of missions scenarios that can be thought of to accomplish with unmanned technology; Improvised Explosive Device (IED) detection, Harbor Patrol, Weather Prediction, Search and Rescue, Hazardous Plum Monitoring, Border Patrol, surveying, Forest Fire Boundary monitoring, etc...The limit seems to be only our own imagination. Of course some of these missions lend themselves to be best performed by one technology or another. However, many missions lend themselves to be best performed by a heterogeneous team of multiple vehicles cooperating to use their strengths most effectively.

At the Autonomous Flight Systems Laboratory (AFSL) we hope to develop the technology to have a fleet of heterogenous vehicles work to together to perform complex missions. UUVs, developed by the Applied Physics Laboratory at the University of Washington, have operated autonomously for 193 straight days [27]. UAVs have been well developed and are currently used all over the world for many different missions. A key bottleneck to achieving the goal of heterogenous teams is the current state of USV autonomy. The ECoPS software has already been well developed for application to UAVs and this thesis presents a step towards applying the same techniques to USVs resulting in increased autonomy.

BIBLIOGRAPHY

[1] U. C. G. Commandant. *International Regulations for Prevention of Collisions at Sea, 1972 (72 COLREGS)*. US Coast Guard, August 1999.

[2] Moire Incorporated. Overveiw of the US Market for Unmanned Surface Vehicles (USVs), October 2003. `http://www.moireinc.com/`.

[3] R. Brizzolara. ONR Unmanned Sea Surface Vehicle (USSV) S & T Program. In *DARPA Alignment Pathway (DAP) Combat Small Boats Industry Day*, Washington, D.C., August 2006. `http://www.marinedd.com/DAPIndustryDaysFY06.html`.

[4] J. Veers and V. Bertram. "Development of the USV Multi-Mission Surface Vehicle III". In *5th International Conference on Computer Applications and Information Technology in the Maritime Industries*, May 2006.

[5] U.S. Dept. of Homeland Security (DHS) and U.S. Dept. of Defense (DOD). *The National Strategy for Maritime Security*, Sept. 2005.

[6] P. Parfomak and J. Frittelli. *Maritime Security: Potential Terrosist Attacks and Protection Priorities*. CRS Report for Congress, Jan. 2007.

[7] J. Larson, M. Bruch, and J. Ebken. "Autonomous Navigation and Obstacle Avoidance for Unmanned Surface Vehicles". In *SPIE Unmanned Systems Technology VIII*, Orlando, FL, April 2006.

[8] A. Maguer, D. Gourmelon, and M. Adatte. "Flash and/or Flash-S Dipping Sonars on Spartan Unmanned Surface Vehicle (USV): A New Asset for Littoral Waters". In *Turkish International Conference on Acoustics*, July 2005.

[9] R. Pap. Unmanned Surface Vehicle (USV). Accurate Automation Corporation. `http://www.accurate-automation.com`.

[10] F. Khorrami. Maritime Seaway Navigation System for Next Generation Unmanned Sea Surface Vehicles. IntelliTech Microsystems, Inc. `http://www.imicro.biz`.

[11] International Submarine Engineering Limited. TC (Tactical Controller) kit. `http://www.ise.bc.ca/TCkit.html`.

[12] C. Lum, R. Rysdyk, and A. Pongpunwattana. "Autonomous Airborne Geomagnetic Surveying and Target Identification". In *Proceedings of the 2005 Infotech@Aerospace Conference*, Arlington, VA, September 2005.

[13] Autonomous Flight Systems Laboratory. `http://www.aa.washington.edu/research/afsl/`.

[14] J. Rubio, J. Vagners, and R. Rysdyk. "Adaptive Path Planning for Autonomous UAV Oceanic Search Missions". In *AIAA 1st Intelligent Systems Technical Conference*, Chicago, IL, September 2004.

[15] R. Rysdyk. "UAV Path Following for Constant Line-of-Sight". In *2nd AIAA Unmanned Systems Conference*, San Diego, CA, September 2003.

[16] D. Rathbun and B. Capozzi. "Evolutionary Approaches to Path Planning Through Uncertain Environments". In *1st AIAA Unmanned Aerospace Vehicles, Systems, Technologies, and Operations Conference*, Portsmouth, VA, May 2002.

[17] J.S. Chahl, L.C. Jain, A. Mizutani, and M. Sato-llic. *Innovations in Intelligent Machines*, chapter 5. Springer, 2007.

[18] A. Pongpunwattana. *Real-Time Planning for Teams of Autonomous Vehicles in Dynamic Uncertain Environments.* PhD thesis, University of Washington, Seattle, WA, June 2004.

[19] D. Rathbun, S. Kragelund, A. Pongpunwattana, and B. Capozzi. "An Evolution Based Path Planning Algorithm for Autonomous Motion of a UAV Through Uncertain Environments". In *AIAA 21st Digital Avionics Systems Conference*, Irvine, CA, October 2002. University of Washington.

[20] Washington State Ferries. *Technical Specification*, July 2006.

[21] National Marine Electronics Association. NMEA 0183 Standard. `http://www.nmea.org/pub/0183/`.

[22] Garmin. *How is the checksum calculated in NMEA 0183*. `http://www.garmin.com/support/faqs/faq.jsp?faq=40`.

[23] S. Showalter. "The Legal Status of Autonomous Underwater Vehicle". *The Marine Technology Society Journal*, 38:80–83, 2004.

[24] S. Lee, K. Kwon, and J. Joh. "A Fuzzy Logic for Autonomous Navigation of Marine Vehicles Satisfying COLREG Guidelines". *International Journal of Control, Automation and Systems*, 2(2), June 2004.

[25] M. Benjamin, J. Curcio, J. Leonard, and P. Newman. "A Method for Protocol-Based Collision Avoidance between Autonomous Marine Surface Craft". *Journal of Field Robotics*, 23(5), May 2006.

[26] A. Chakravarthy and D. Ghose. "Obstacle Avoidance in a Dynamic Environment: A Collision Cone Approach". In *IEEE Transactions on Systems, Man, and Cybernetics - Part A: Systems and Humans*, volume 28, September 1998.

[27] Applied Physics Laboratory. `http://www.apl.washington.edu/projects/seaglider/summary.html`.

[28] R. Rysdyk, C. Lum, and J. Vagners. "Autonomous Orbit Coordination for Two Unmanned Aerial Vehicles". In *Proceedings of the AIAA Guidance, Navigation, and Control Conference and Exhibit*, San Francisco, CA, August 2005.

[29] U.S. Coast Guard Navigation Center. AIS Overview. `http://www.navcen.uscg.gov/enav/ais/default.htm`.

[30] U.S. Coast Guard Navigation Center. What AIS Broadcasts. `http://www.navcen.uscg.gov/enav/ais/what_AIS_broadcasts.htm`.