ASSESSING AUTOMATED AND HUMAN PATH PLANNING FOR THE SLOCUM GLIDER

Hans Christian Woithe
Rutgers University
hcwoithe@cs.rutgers.edu

Mike Eichhorn
Institute for Automation and Systems Engineering
Ilmenau University of Technology
mike.eichhorn@tu-ilmenau.de

Oscar Schofield
Institute of Marine and Coastal Sciences
Rutgers University
oscar@marine.rutgers.edu

Ulrich Kremer
Rutgers University
uli@cs.rutgers.edu

Abstract

Autonomous Underwater Vehicles (AUVs) are a common tool used by oceanographers to study oceans. Most AUVs are operated by pilots who are able to interpret environmental information to make effective mission decisions; this function requires an understanding of the hardware and software of these complex systems. To enable oceanographers and pilots to more easily manage a fleet of gliders, new mechanisms are needed to ease the burden of AUV operation. An automated path planning system is one such tool that could free operators from the tedious task of waypoint selection, and would allow them to focus on scientific and mission critical aspects of managing groups of AUVs.

AUV path planning involves selecting a set of waypoints to guide an AUV from a starting location to a destination location while considering obstacles such as shipping lanes, ocean currents, or limited battery resources. Offloading operational tasks to an automatic tool is only feasible if the decisions made by the tool are considered reasonable and can be trusted. We have developed a testbed environment to assess the flight paths and energy consumptions of both an AUV guided by an automated path planning system and human pilots. The testbed environment is based on a new, faster-than-real-time, software only, simulator for the Slocum Glider. In an effort to evaluate this simulator, four pilots with varying backgrounds and glider flight experiences were asked to fly a Slocum glider through a simulated Gulf Stream modeled current field. The same challenge was posted to an automatic path planning system currently in development. The results of our study demonstrate that the automatic path planning system performed on par with experienced pilots. Furthermore, the testbed environment revealed a problem with the existing ocean current correction system used by the commercially available glider. Using our simulation testbed, we were able to develop and test an alternative heading algorithm.

1 Introduction

Autonomous underwater vehicles (AUVs) have evolved from mainly experimental platforms to increasingly reliable systems that allow a continuous sensing presence in the world's oceans. Individual AUV deployments can typically last weeks and even several months. As AUV technology matures, we expect a shift from mainly hardware and basic system challenges to the challenge of effectively operating individual or groups of vehicles. The lifetime costs of current and future AUVs will be dominated by the cost of operating them, rather than the cost of purchasing and maintaining the vehicles.

Operating costs of an AUV include expenses for deployment, recovery, batteries, satellite communication, and insurance, but the largest cost can be attributed to the pilots who remotely monitor and control the vehicle. Based on our survey among Teledyne Webb Research's Slocum glider pilots, a well-trained pilot can operate between one and eight gliders, depending on the particular glider missions and environmental challenges (e.g., navigating through an eddy field, shipping lanes, or through a severe weather front). Pilot fatigue, dealing with vehicular emergency conditions, or distractions by other tasks can interfere with the safe operation of even a single glider. Therefore, there is a strong need for tools that can help pilots control large fleets of AUVs more efficiently. These tools may range from fully automatic flight path and resource planning, to tools that only suggest action plans to the pilot who is tasked with making the final decision.

Determining the best flight path to fly from point A to point B is a difficult challenge. Vehicular, environmental, and mission-specific models and parameters need to be considered. Pilots typically do not have perfect knowledge about the physical environment or the particular flight characteristics of a glider. For instance, there may be some information available about the current and predicted surface currents (CODAR [1]), but the underwater currents are unknown or only approximated (HYCOM [2]). No two gliders fly the same way due to differences in ballasting, buoyancy, and payload characteristics. Such unknowns can lead to errors in flight predictions that can add up quickly. Having the glider resurface in short intervals can limit the propagation of these errors, but can also significantly reduce the effectiveness of missions. Finally, gliders are battery operated, so effective energy management is a crucial concern. The energy consumption of a glider greatly depends on the activities and mutual interactions of motors, sensors, and the low-level software components (drivers) that control them. Thus, an ideal automatic path planner should be able to guide the AUV in non-critical situations, while only assisting pilots in critical situations. This will enable pilots to be more efficient by allowing them (1) to focus their attention on situations where their expertise is really needed, and (2) to make better informed and faster decisions.

In this paper, we investigate how a faster-than-real-time, full software stack simulator and an advanced path planning algorithm can be used to guide a glider through a meander that is represented by a three-dimensional (3D) Gulf Stream model [3]. To the best of our knowledge, this is the first attempt to compare the quality of an automatic strategy versus human pilots for the Slocum glider. The faster-than-real-time, full software stack simulator for the Slocum glider is currently under development by our group. The simulator includes vehicular, environmental, and energy models to determine the behavior of a glider while flying from one waypoint to another.

During the course of this study, we recognized that there were mismatching assumptions made by the pilot and the automatic path planning tool. This illustrates a crucial benefit of our new environment, namely its capability to identify strengths, weaknesses, and other "performance" characteristics (e.g., precision, speed, safety) of a pilot's decision process or of an automatic path planning algorithm. Specifically, we identified a problem with the heading correction algorithm used by the glider as part of its ocean current correction strategy. Current correction is a standard software module used by the gliders. The heading correction algorithm was fixed, and installed in the glider's system software stack that runs on our simulator. Using the new heading correction module, the fully automatic path planner was able to produce high quality flight paths comparable to or even better than those generated by experienced pilots. The main contributions of this paper include:

- A new heading correction algorithm that has been integrated in the Slocum glider system. The simulation infrastructure is used to showcase an issue with the existing heading algorithm and to evaluate our solution.
- A study of glider pilot performance and decision making based on a realistic flight path problem.
- An analysis of glider pilot performance relative to an automatic path planning system that makes use of the heading correction algorithm.

The presented study is preliminary since it only involved an evaluation of four glider pilots. However, we believe that simulation testbeds such as the one discussed in this paper are crucial to facilitating pilots with different backgrounds and experiences to do their job more effectively, and glider software developers to debug and test new software modules. Since our simulator is software-based, hundreds of test flights may be performed at the same time using modern multi-core processors, thereby significantly reducing testing and verification times.

2 Background

2.1 The Slocum Glider

The Slocum Electric Glider is an AUV developed and produced by Teledyne Webb Research[4] that belongs to a class of buoyancy driven AUVs which includes vehicles such as Bluefin Robotics' Spray Glider [5] and iRobot's Seaglider [6]. A Slocum glider with a double payload bay is shown in Figure 1. A buoyancy engine at the front of

Figure 1: A Slocum Glider equipped with a double payload bay and an acoustic modem.

the vehicle moves a piston to change the vehicle's displacement of water, allowing for vertical motion in the water column. The pitch of the AUV may be fine-tuned by moving an internal battery pack, thereby changing its center of gravity. The vehicle's wings allow it to glide forward through water to produce a saw-toothed flight profile inflecting near the surface and at deeper depths. Using a rudder and the global positioning system (GPS), the glider is able to navigate and collect data samples using onboard sensors. Satellite and radio communications are used at the surface to transfer scientific and vehicle data, and if necessary, to alter the AUV's mission [7]. The Slocum glider, despite being generally slower than propeller driven vehicles, with an approximate speed of 35 cm/s, has the advantage of requiring much less power. The buoyancy engine is required only during inflection points, which may be as shallow as a few meters below the surface or as deep as 200 meters for a coastal glider. This produces prolonged flights typically lasting weeks or even months [7] depending on sensor payload and sensor usage.

2.2 Path Planning

Path planning is an important requirement for an autonomous mobile system, and is necessary to effectively navigate a vehicle during a mission.All current and future information about the area of operation and the vehicle's status are used to formulate a path. In the case of AUVs, information about the area of operation can be gathered from ocean models and from measurements derived by the AUV itself. Other important vehicle properties, such as its speed and energy consumption, are also important components to consider to effectively plan a course [8].

The goal of the path planning algorithm used in this paper is to find a time-optimal path from a start position to a goal position by evading all static and dynamic obstacles in the area of operation, while considering the dynamic behavior of the vehicle and the time-varying ocean current. This path planning algorithm, named the Time Variant Environment (TVE) algorithm [3, 9], is based on a modified Dijkstra algorithm [10]. A time-variant cost function is included in this algorithm, which will be calculated during the search to determine the travel times (cost values) for the examined edges. This modification allows a time-optimal path to be determined in a time-varying environment. In [11], this principle was used to find the optimal link combination to send a message via a computer communication network with the shortest transport delay.

The path algorithm uses a geometric graph for the description of the area of operation with all its characteristics. The defined points (vertices) within the operational area are those passable by the vehicle. The passable connections between these points are recorded as edges in the graph. Every edge has a rating (cost, weight) which is the time required for traversing the connection. In the case of an ocean current, the mesh structure of the geometric graph will be a determining factor associated with its special change in gradient. In other words, the defined mesh structure should describe the trend of the ocean current flow in the operation area as specifically as possible. A uniform rectangular grid structure is the easiest way to define such a mesh.

3 Glider Simulator

The Slocum glider uses a layered-control programming architecture that determines mission sensing and control actions in cycles. Typically, the duration of a cycle is four seconds. During these four seconds, a rather complex interaction among different drivers for sensors, motors and software components is performed. These complex software and hardware interactions make it difficult to design a high-level behavior model of all activities. Instead of modeling the software and its behavior on the vehicle, we run and monitor a portion of the glider's software system. The presented study is based on a faster-than-real-time, full software stack simulator for the Slocum glider currently under development by our group. The simulator includes vehicular, environmental, and energy models to determine the glider's behavior during mission execution and is capable of running on commodity hardware.

A typical Slocum simulator is either a physical glider on a bench top running in simulation mode, a "Shoebox" simulator, or a "Pocket" simulator. A "Shoebox" simulator contains much of the electronics of a glider contained in shoebox sized container, while the "Pocket" simulator contains the bare minimum amount of electronics to run the glider's software. These simulators run in real-time, so testing long term missions can be cumbersome, if not infeasible.

We were motivated to port the Slocum glider software because much of our previous work involved developing and integrating new functionalities into the vanilla software system. Having modern tools available eases development and testing. For example, we are capable of using modern debuggers and can inject data to test the vehicle's software using synthetic data and data from previous deployments. Thus, much of the interoperability can be accomplished on a modern desktop before ever testing it on an actual vehicle.

Because the glider software is no longer tied to the glider's hardware and development stack, it can be easily extended to include additional features. In particular, one useful extension that we have added is the ability to run the simulator in a faster-than-real-time mode. Depending on the specifications of the host computer running the simulator, we have simulated up to 30 mission hours in one minute, a three order of magnitude (1800x) speedup over a "Pocket" or "Shoebox" simulator. This enables long-term missions to be easily and quickly tested.

Furthermore, we have implemented a hybrid mode that simulates faster-than- real-time while underwater, and real-time while at the surface. In this mode of operation, a glider pilot can conveniently interact with the simulated glider while at the surface, for example to change mission parameters, while quickly simulating the underwater flight segment where no satellite communication is possible. For the experiments presented in this paper, this is the default mode of operation.

An important aspect to any deployment is to monitor and estimate a vehicle's energy consumption. In previous work, [8], we deployed a glider off the coast of New Jersey to measure the power dissipation of the individual components of the AUV during its mission. These measurements were used to build energy models that can be used to estimate the energy expended by analyzing the glider's log files. Like the glider, our simulator generates these log files which can be used by the energy model. We have integrated a service into the simulator code that will execute the energy model during flight and present it as a glider sensor to facilitate evaluation. These mechanisms are used in our evaluation to provide a sense of the energy dissipation during each stage of a mission.

4 Current Correction System

During typical glider operations, the AUV is tasked to fly to a list of waypoints. Pilots may choose to navigate with the feature of current correction (CC) enabled or disabled. When enabled, the vehicle's software will use its estimates of the water current components in its dead reckoning (DR) and heading calculations. When disabled, the water current is not considered in either the DR or heading calculation.

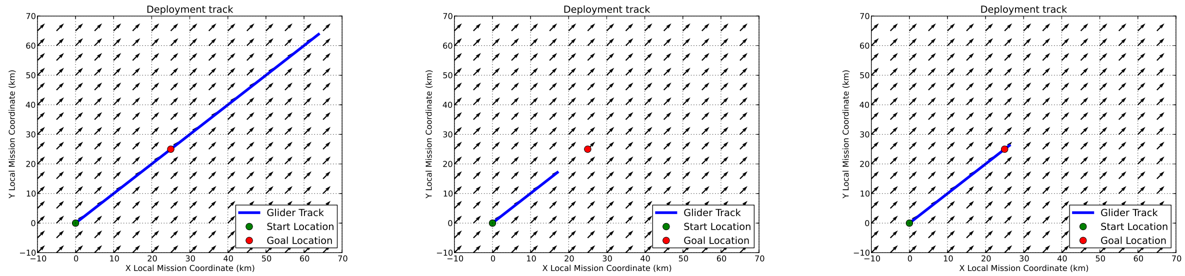
Based on the feedback from several experienced glider pilots, we learned that some missions are flown, in part, without the use of CC. These pilots expressed that, at times, they had difficulty navigating the vehicle while the CC feature was enabled and therefore fly without it in some situations. We would, however, like to navigate with CC to ensure that the vehicle follows the track as specified by a path planning system.

We investigated the CC algorithm implemented in the Slocum using our simulator flying in the faster-than-real-time mode. Two nearly identical mission files were created to fly the vehicle from a starting location to a northeast target waypoint approximately 35 km away. The mission files only differ in that one has CC enabled while the other does not. A favorable current in the direction towards the target waypoint was set in the simulator with a speed of 50 cm/s, which is larger than the average speed of the glider. We flew three missions: with CC disabled; with CC enabled; and with CC enabled but with the alternative heading algorithm (described in Section 4.1). This algorithm is also used in the evaluation of the automated path planning system.

The flight tracks of the simulated Slocum glider's missions are shown in Figure 2. These tracks are of the actual paths of the vehicles and not their DR paths. In Figure 2(a), with current correction disabled, the glider vastly overshoots the target waypoint. When disabling CC, the glider assumes in its DR calculations that the water current components are both zero. Therefore, in strong currents, the DR position of the glider can grow to be significantly different than that of the AUV's actual position. In the sample mission, the vehicle will continue to fly and only surface to complete the mission when it believes it has arrived at the waypoint. Thus, if the AUV's DR positioning is highly inaccurate it cannot effectively navigate itself to the target.

Figure 2(b) shows the flight path with the standard CC system enabled. The heading algorithm is executed periodically to adjust the glider's flight path towards the target waypoint. The algorithm first calculates the expected flight time to reach the waypoint using the AUV's average speed with no consideration of the sea current. Then, using this flight time, the algorithm offsets the target waypoint by the displacement caused by the current during that time. The heading to the new offset waypoint is calculated and used to fly the glider. As seen in Figure 2(b), the glider falls short of reaching its intended target. Because the current speed is greater than the vehicle's average speed, the heading algorithm actually caused the AUV to fly directly straight into the current, i.e., in the opposite direction away from the target. This simple scenario highlights the problem with standard CC system.

We implement an alternative heading algorithm, described in Section 4.1, to adjust the glider's course in the



(a) Current correction disabled.

(b) Default current correction algorithm.

(c) Current correction enabled with the new heading correction algorithm.

Figure 2: The path taken by three flights flying a sample mission tasked to fly to a waypoint 35 km north-west with a current of 50 cm/s.

simulator. The path taken by the vehicle with the modified CC system is shown in Figure 2(c). The vehicle maintained a direct heading towards the target and arrived at the waypoint in the shortest time of the three flight scenarios.

4.1 Heading Algorithm Description

In the previous section, we demonstrated how the existing heading algorithm incorrectly guides the vehicle to fly directly against a favorable current. Here, we describe the algorithm implemented in the simulator that was used for the automated path planning flights. Though the path planning system described in Section 2.2 offers the ability to generate waypoints offset by the water current conditions, we wanted to explore a more general solution for the AUV for future inclusion into the glider's software.

The glider heading φ to follow a defined path can be calculated to include the ocean current vector $\mathbf{v}_{current}$ and the path/course vector $\mathbf{v}_{path}$. This path vector can be described by a magnitude and a direction. The direction is defined by a unit vector $\mathbf{v}^0_{path}$ of a point subtraction of the target waypoint and the current vehicle position. The magnitude of the path vector is the speed which the glider travels on the path in relation to a fixed world coordinate system. This speed v_{path_ef} depends on the vehicle speed through the water v_{veh_bf} (cruising speed), the magnitude, and the direction of the ocean current vector, as well as the direction of the path $\mathbf{v}^0_{path}$. This speed can be determined by the intersection point between a line and a circle (2D) and/or sphere (3D) [12], based on Figure 3(a), according to the following relation (1):

$$\begin{aligned} &line\colon \mathbf{x}\left(v_{path\_ef}\right) = v_{path\_ef}\mathbf{v}^0_{path} \\ &circle/spheres\colon v^2_{veh\_bf} = \left\|\mathbf{x} - \mathbf{v}_{current}\right\|^2 \end{aligned} \tag{1}$$

$$\begin{aligned} disc = {}& ({\mathbf{v}^0_{path}}^{\mathbf{T}} \cdot \mathbf{v}_{current})^2 \\ &+ v^2_{veh\_bf} - {\mathbf{v}_{current}}^{\mathbf{T}} \cdot \mathbf{v}_{current} \end{aligned} \tag{2}$$

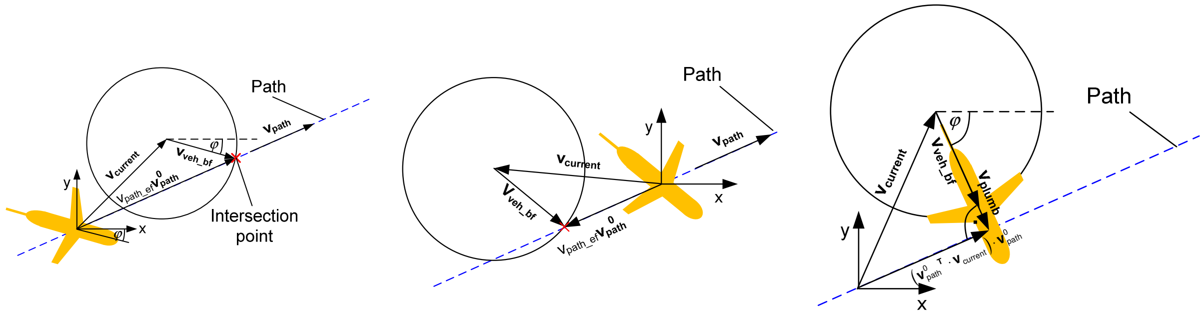
If the discriminant $disc$ in Equation (2) is positive, the glider heading φ can be calculated using the following equations (3):

$$\begin{aligned} &\text{if } disc > 0 \\ &v_{path\_ef} = {\mathbf{v}^0_{path}}^{\mathbf{T}} \cdot \mathbf{v}_{current} + \sqrt{disc} \\ &\mathbf{v}_{veh\_bf} = v_{path\_ef}\mathbf{v}^0_{path} - \mathbf{v}_{current} \\ &\mathbf{v}_{veh\_bf} = \begin{bmatrix} x_{v\_veh\_bf} \\ y_{v\_veh\_bf} \end{bmatrix} \\ &\varphi = \text{atan2}(y_{v\_veh\_bf}, x_{v\_veh\_bf}) \end{aligned} \tag{3}$$

If the speed v_{path_ef} is negative, the vehicle is still on the path, however, it is moving backwards. This scenario is shown in Figure 3(b).

If the discriminant $disc$ in Equation (2) becomes negative, v_{path_ef} does not have a real solution. This means that the vehicle cannot be held in that path and so the path is not feasible. This scenario is depicted in Figure 3(c). In this case, the calculated heading results in a "closest point on the line" calculation. The resulting glider heading is perpendicular to the path so that the drift to the desired path is minimal. This can be calculated using the following equations (4):

$$\begin{aligned} &\text{if } disc \leq 0 \\ &\mathbf{v}_{plumb} = \left({\mathbf{v}^0_{path}}^{\mathbf{T}} \cdot \mathbf{v}_{current}\right) \cdot \mathbf{v}^0_{path} - \mathbf{v}_{current} \\ &\mathbf{v}_{plumb} = \begin{bmatrix} x_{v\_plumb} \\ y_{v\_plumb} \end{bmatrix} \\ &\varphi = \text{atan2}(y_{v\_plumb}, x_{v\_plumb}) \end{aligned} \tag{4}$$



(a) Definition of the velocities

(b) Negative v_{path_ef}

(c) Negative discriminant

Figure 3: Velocity relationships.

5 Evaluation

The aim of the presented evaluation results are not to criticize a particular path planning strategy, whether it is human piloted or piloted by a path planning algorithm. Rather, we aim to provide the capability and technology to evaluate these strategies. In the case of human piloted flights, we provide a graphical interface that interacts with the simulator discussed in Section 3. For the automated flight, a tool interacts with both the simulator and the path planning program described in Section 2.2. In both cases, the simulator was modified for the evaluations as described in the following sections.

5.1 Simulator Modifications

For the evaluation, we have integrated the new heading algorithm discussed in Section 4.1. Current correction was not used for the human piloted missions as some of the more experienced pilots preferred to fly without it for the current model used in the evaluation. The algorithm was, however, enabled for the automated flight. Although the path planning tool has been augmented to provided waypoints with the correct current offsets, we wanted to evaluate a more generalized solution for the vehicle.

One advantage of running a full software-stack simulator is that specific hardware and software parameters can be easily adjusted to better reflect the flight characteristics of a particular glider. For example, the vehicle's simulation driver determines the speed of the glider through the water using the AUV's pitch and change in depth. The pitch and depth rate are in turn functions of the vehicle's pitch battery and buoyancy pump positions. In a stock simulator, the models that map motor positions to the pitch and depth rate are based on a flight from Buzzards Bay in 2002. Because we also use the simulator to study past and live deployments, we have retrofitted the pitch and depth rate models after a two week flight of Rutger's RU06 glider off the coast of New Jersey.

The Slocum glider model from Buzzards Bay (BB), while valid, is not a generalized model. Each particular glider can fly very differently depending on, for example, how it was ballasted. According to the log files, the RU06 appears to be too positively buoyant; the vehicle spent over 70% of its time in the diving state rather than an even time in the diving and the climbing states.

Using linear regression in the Weka data mining software, [13], we created two models for the vehicle. First, a battery and buoyancy pump position to pitch model, and second, a pitch and buoyancy pump position to depth rate model. We compare the predicted pitch and depth rate of the models to the vehicle's log files. The average predicted error for the new pitch model when compared against the vehicle's log files is 3.5° compared to 10.2° of the BB model. Most of the errors in the new model occur during inflections, while in the BB model, the errors lie in the misprediction of the climb angle. The error of the depth rate models is 6 cm/s for the new model compared to 18 cm/s for the BB model. The high error in the BB model is likely due to RU06 being too positively buoyant, and the diving depth rate being much lower than that of the glider in Buzzards Bay. Nonetheless, this does not invalidate the BB flight model as a model to be used for the simulator, but it does showcase the importance of tuning such models to more closely reflect the nuances between particular gliders. We use these RU06 models throughout our evaluation although the BB model could have been used instead.

The stock software allows a fictitious sea current to be specified. However, this current is static until it is explicitly updated by the user. In Section 4, this static current specification was used to study the stock glider's heading algorithm. To increase the realism of the experiments, we have modified the simulator to dynamically change the currents in an effort to reflect a 3D Gulf Stream current model [3]. Other model data could have been injected, but we chose to use this model as it was already integrated as one of the testing environments in the path planning tool.

5.2 Piloting Tools

To ease the evaluation on the human test subjects, we chose to use the simulator in the hybrid mode that simulates glider flight faster-than-real-time while underwater and in real-time at the surface. Typically, pilots interact with the glider using the manufacturer provided Dockserver mission control system. However, we have not be able to create a good user experience with the Dockserver if the simulator is running in any faster-than-real-time mode. Alternatively, we interact with a simulated glider's terminal with the Pexpect Python module, commonly used to control and automate programs. Because Pexpect launches the simulator as a subprocess, it is still necessary to slow the simulator down while at the surface. If it is not slowed, the monitoring program will not be able to communicate with the AUV in time before the vehicle continues onto the next mission segment.

In lieu of the pilots taking over control of the glider at the surface, we also created a graphical user interface to send and receive vehicle events and messages to and from the terminal monitoring program. This GUI tool is shown in Figure 4(a). As described, the automated path planning tool also uses the Gulf Stream model in its calculations. Thus, we provide the human pilot with a graphical depiction of the surface currents that will occur within the next 20 days. It is common for pilots to overlay ocean current model data in applications such as Google Earth to assist them in their waypoint generation. Although we extend the presented model prediction to 20 days, thereby creating an atypical advantage compared to a real deployment, we feel it is justified considering that the path planning tool knows about the model and the pilots were unfamiliar with the area of operation.

In the interface, pilots can use the slider beneath the current plot to see the surface currents at any particular time. Note that the Gulf Stream model is a 3D model and it applies currents to the simulated glider at all depths. Hovering the mouse over the plot updates the GUI with the water current information at that location and at the time specified by the slider. The vehicle's mission time and distance to the next waypoint is also shown which provides additional feedback to the user about the deployment. If the pilot wishes to plot the surface currents that are being applied to the glider, the reset button can readjust the current field slider to the glider's current mission time.

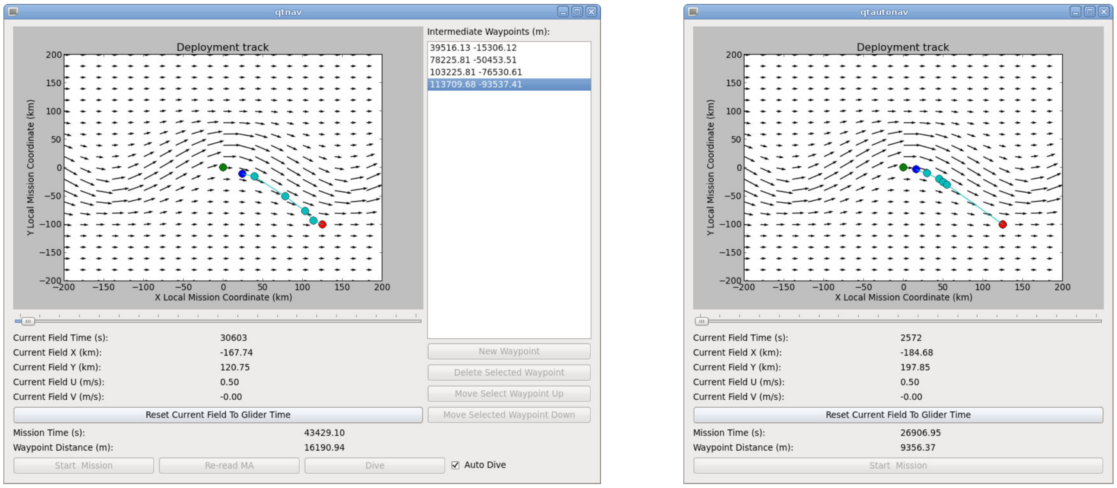
New waypoints can be added and deleted using the tools on the right-hand side of the interface and by selecting current field plot. In Figure 4(a), the start location is indicated by the green indicator, the destination by a red indicator, and intermediate waypoints, specified by the user, as cyan indicators and lines. Any modifications to the waypoints list requires the user to explicitly click the "Re-read MA" button to have the program generate a new mission argument list, send it to the AUV, and have it re-read and update the mission's behaviors.

The mission arguments for the waypoint list sent to the glider are in the glider's local mission coordinates (LMC) system. This is unconventional, and the simulator was extended to support this feature. Typically, only waypoints specified via latitude and longitude are supported in the goto list behavior's mission argument file. This was done purely for convenience so that the Gulf Stream model and the path planning system can both use the same coordinate system.

Users of the tool can only send new waypoint lists when the simulated glider is at the surface. To instruct the glider to continue onto the next dive segment, each lasting four hours, the pilot can click the "Dive" button. If no changes are expected for several dive segments, the "Auto Dive" checkbox will have the GUI tool instruct the glider to continue its mission on behalf of the pilot. If a modification to the mission is required, unchecking this box will allow the pilot to manually re-task the AUV at the next surfacing.

The interface of the automated path planning tool is shown in Figure 4(b). The interface presented is very similar to that of the human piloting tool. Although having a GUI is not required, it aids in debugging and development to ensure that the expected waypoints are generated and flown. There is also a "headless" version of the automated path planning system that does not use a GUI. The headless version is helpful in parameter space exploration and has been deployed on a compute cluster where multiple path planning algorithms can execute at the same time.

The automated flight program also uses the monitor program in place of Dockserver to control the glider's terminal. During the simulated mission, when the AUV comes to the surface, the vehicle's current waypoint and mission time are used as input when executing the path planning program. The produced plan is reduced to only a few waypoints as the glider's software system is restricted to only a small list of points. Waypoints that are close to one another are also reduced. Despite not executing the exact track generated by the path planning system, we wanted to work within the constraints of the glider. Most of the extensions made to the vehicle's software have so far been made for the evaluation and so we limit ourselves here because we aim to use the same path planning infrastructure to guide a fleet of gliders. While the path planning system has the opportunity to re-task the vehicle every time it surfaces, in a real deployment, commu-



Intermediate Waypoints (m):

39516.13 -15306.12
78225.81 -50453.51
103225.81 -76530.61
113709.68 -93537.41

Current Field Time (s):	30603
Current Field X (km):	-167.74
Current Field Y (km):	120.75
Current Field U (m/s):	0.50
Current Field V (m/s):	-0.00
Mission Time (s):	43429.10
Waypoint Distance (m):	16190.94

(a)

Current Field Time (s):	2572
Current Field X (km):	-184.68
Current Field Y (km):	197.85
Current Field U (m/s):	0.50
Current Field V (m/s):	-0.00
Mission Time (s):	26906.95
Waypoint Distance (m):	9356.37

(b)

Figure 4: (a) The graphical user interface used by a human pilot to help navigate a simulated glider from the green starting waypoint to the red destination waypoint. Intermediate waypoints selected by the pilot are drawn using cyan indicators and lines. The automated tool, (b), uses path planning software to determine intermediate waypoints.

nicating with the AUV may not always be possible and so our revised plan always ensures that the final destination waypoint is also always included.

5.3 Results and Discussion

For the human piloted missions, we asked four subjects to traverse a meander in the Gulf Stream model with the aid of the graphical tool shown in in Fig. 4(a). The four pilots had many years of glider flight experience between them, ranging from over ten years to just a few hours. All subjects have been working in oceanography for years as physical or biological oceanographers, or oceanographic technicians.

Before starting the experiment, each subject was given a brief tutorial on the usage of the tool and was allowed to briefly experiment with it. The subjects were encouraged to use the current field slider to gain some insight of the currents in the area of operation. The pilots were also instructed to fly from the starting location to the end point in the minimum amount of time, while prioritizing the safety of the vehicle as if it were a real deployment.

The simulated mission was based off of a previously deployed flight. The glider was instructed to fly at a diving and climbing angle of 26° between 5–95 m. The water depth was set to 200 m so that the vehicle would not have to inflect early to avoid hitting the ocean bottom. Finally, the simulated glider is equipped with two backscatter and fluorometer sensors.

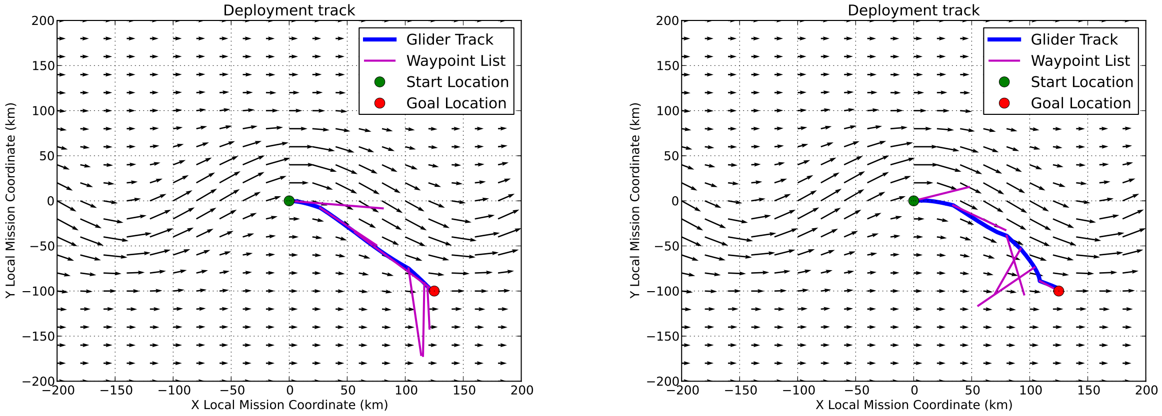
Pilot	Time (d)	Energy (kJ)
A	3.07	595.26
B	3.34	649.17
C	3.27	636.26
D	3.15	612.32
Auto	2.92	571.47

Table 1: Results of human piloted flights and the automatic path planner (Auto).

Table 1 shows the summary of the evaluation. Several subjects performed the experiments more than once. In these cases, we present the deployment that had the shortest flight time. Subject D performed the experiment once, subjects A and C twice, and subject B three times. Admittedly some subjects expressed they were slightly more aggressive, but within reason, on repeat attempts. This is likely due to their increase in comfort in using the tool and knowing that the AUV is indeed not real.

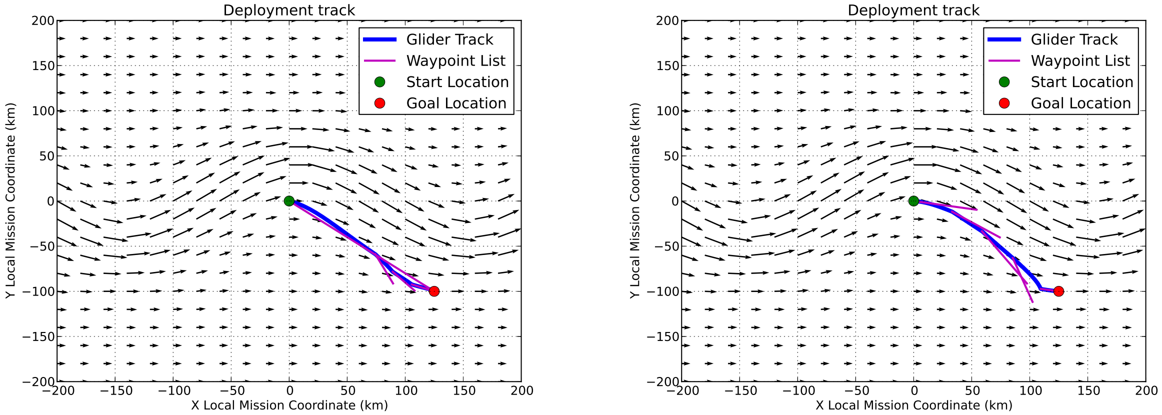
The human generated flight paths ranged in duration from 3.07 days to 3.34 days, with overall energy consumption between 595 kJ and 649 kJ. The selected end waypoints were chosen specifically with the knowledge that if no action is taken by the pilot and no intermediate waypoints are provided, the glider would still make it to its destination in a sub-optimal amount of time and energy. The results of this "hands-off" approach was a flight time of 3.38 days with an energy expenditure of 657 kJ. Two of the pilots, B and C, discovered this approach on their first attempts.

For two out of the three subjects who performed multiple evaluations, the pilots were successful in decreasing their flight time on each successive attempt and thereby also reducing the energy dissipated. Subject B, after dis-



(a) Pilot A

(b) Pilot B



(c) Pilot C

(d) Pilot D

Figure 5: The flight tracks of the simulated flights by human pilots.

covering the “hands-off” approach on their first attempt, did not improve their mission time on their second try. However, the subject quickly turned things around on the third attempt and bested their previous two flights.

The flight tracks of the missions of Table 1 are shown in Figure 5. As previously mentioned, the green indicator represents the start location of the mission and the red indicator the destination location. The blue lines show the path taken by the vehicle. The magenta line segments represent the assigned waypoints from the current glider location to the next waypoints. Thus, the start of a line segments is the current glider location on the track when the waypoint was assigned, and the end of a line indicates the first of the assigned waypoints. We only show the first assigned waypoint at each re-tasking to reduce the number of lines in the figure.

For the human piloted flights, the current correction algorithm was disabled as suggested by the more experienced pilots. None of the test subjects seemed to have any qualms regarding this constraint and we observed that compensating for current seemed natural to pilots. With repeated experiments, we perceived that the subjects were quickly refining this skill. In one particular case, a pilot quickly adapted and seemed to begin to emulate the navigation characteristics of one the more experienced subjects. We found this especially interesting since the evaluations took place independently so that no one subject could learn from another.

In the flight paths show, in Figure 5, three of the four pilots tried to use the meander to their advantage as a more favorable current towards the target waypoint. Subject C, who used the “hands-off” approach on their first attempt (not shown), noticed that the vehicle slightly missed the target waypoint and had to backtrack. On their second attempt, Figure 5(c), they piloted mostly “hands-off” for much of the flight but tried to prevent the back tracking

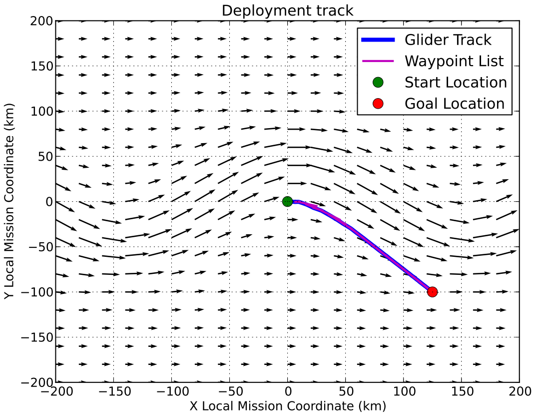


Figure 6: The deployment track of an automated path planning system piloting the simulated mission.

from east to west by changing course and flying south earlier.

Pilots A and D had similar flight paths and the two best mission times. Both decided to use the meander but were cautious not to get into currents too strong that would be difficult to escape from. It appears that Pilot A, Figure 5(a), was able to hug the meander longer than Pilot B in the mission of Figure 5(d) and so was able to clench a better time.

Subject B in the attempt shown in Figure 5(b) improved on the two previous flights. The subject was initially more aggressive than the other pilots by flying the deepest into the meander. However as they approached the destination it had become clear that if they were not careful they would be swept up. The pilot cautiously executed an escape maneuver, wanting not to put the mission at risk. The AUV was safely able to reach its destination in a respectable time.

The result of a completely automated path planning mission has a flight time of 2.92 days with an energy consumption of 571 kJ as shown in Table 1. The track flown by the vehicle is show in Figure. 6. Because the path planning system had an opportunity to refine its path planning at every surfacing, we observe many waypoint list adjustments. Like the human subjects, the AUV was tasked to fly slightly into the meander for the additional speed. The path planning was also successful at navigating the glider out of the strong currents and to its destination.

Despite accomplishing a respectable flight time, we feel further revisions on both the glider and the automated flight system could produce even better times. The result shown required some exploration of the parameter space in the path planning tool and the automated testing program. With further adjustments we hope to reduce or eliminate this exploration. For example, the automated testing tool could use the glider's observed average speed and provide it to the path planning system at each surfacing. The speed model in the path planning system itself could also be improved, for example, by creating a customized speed model as described in Section 5.1. Finally, the path planning tool could provide the glider with sea current information that it will experience within the coming flight segment instead of using sea current information from the prior segment.

6 Conclusions and Future Work

In this paper, we have described our ongoing work in porting the Slocum glider software to create a development, integration, and testing infrastructure. We extended the standard glider simulator in several ways for our assessment of human and automated navigation. A customized flight model, based on logged data from a previous deployment, was used in place of the existing model. The simulated vehicle also flew in a 3D Gulf Stream current model with an alternate heading model to assist in steering.

To assess the flights of both human subjects and the automatic planning system, we created two GUI programs to interact with the various software components. Four pilots took part in the human evaluation. The pilots performed admirably with the best time of 3.07 days, however, they were unable to accomplish a shorter flight time than the automated system's 2.92 days.

As we have described, experienced glider pilots express that they would not fly the Gulf Stream model used in the evaluation with the existing current correction scheme enabled. We have not yet had the opportunity to repeat the human piloted experiments using a glider simulator with the heading algorithm described in Section 4.1. It would be an interesting exercise to observe whether the pilots adjust to the alternate heading algorithm or if they feel more comfortable accounting for the current themselves. The pilots would likely require some time to adjust to the new flying behavior before confidently navigating with it in any real world scenario.

In the evaluation, we alluded that many improvements could be made to decrease the flight times and increase the robustness of the automatic planning system. We hope, for example, if the current model data exists for the area of operation, the planning system could provide the average current the AUV would experience in the following segment to the vehicle. The glider could use this information in its current correction system to assist the vehicle to maintain the flight track laid out by the path planner. We hope to investigate such open issues as we develop the technologies and algorithms to integrate the path planning system for future, real world glider operations.

Finally, the test subjects expressed their belief that the automatic and human path planning programs would also be useful as educational tools. Since the water current or other environmental data can easily be injected into the simulator, one can imagine creating a set of predetermined testing environments that could be used to assess the decision-making skills of pilots in a diverse array of situations.

Acknowledgement

We would like to thank the anonymous oceanographers and glider pilots for taking the time to evaluate our simulation testbed, and for many useful insights and comments.

References

[1] Rutgers University, Coastal Ocean Observation Lab, "CODAR," http://marine.rutgers.edu/cool/codar.html.

[2] H. consortium, "HYCOM," http://www.hycom.org/.

[3] M. Eichhorn, C. Williams, R. Bachmayer, and B. de Young, "A mission planning system for the AUV "SLOCUM glider" for the Newfoundland and Labrador shelf," in *OCEANS 2010 IEEE - Sydney*, pp. 1–9, 2010.

[4] Teledyne Webb Research, "Slocum glider," (Falmouth, MA). http//www.webbresearch.com/slocum.htm.

[5] J. Sherman, R. Davis, W. B. Owens, and J. Valdes, "The autonomous underwater glider "spray"," *Oceanic Engineering, IEEE Journal of*, vol. 26, no. 4, pp. 437–446, 2001.

[6] C. C. Eriksen, T. J. Osse, R. D. Light, T. Wen, T. W. Lehman, P. L. Sabin, J. W. Ballard, and A. M. Chiodi, "Seaglider: A long-range autonomous underwater vehicle for oceanographic research," in *IEEE Journal of Oceanic Engineering*, vol. 26, October 2001.

[7] O. Schofield, J. Kohut, D. Aragon, L. Creed, J. Graver, C. Haldeman, J. Kerfoot, H. Roarty, C. Jones, D. Webb, and S. Glenn, "Slocum gliders: Robust and ready," *Journal of Field Robotics*, vol. 24, no. 6, pp. 473–485, 2007.

[8] H. Woithe, I. Chigirev, D. Aragon, M. Iqbal, Y. Shames, S. Glenn, O. Schofield, I. Seskar, and U. Kremer, "Slocum glider energy measurement and simulation infrastructure," in *OCEANS 2010 IEEE - Sydney*, pp. 1–8, May 2010.

[9] M. Eichhorn, "Optimal Path Planning for AUVs in Time-Varying Ocean Flows," in *16th Symposium on Unmanned Untethered Submersible Technology (UUST09)*, (Durham NH, USA), August 23-26, 2009 2009.

[10] E. W. Dijkstra, "A Note on Two Problems in Connexion with Graphs," *Numerische Mathematik*, no. 1, pp. 269–271, 1959.

[11] A. Orda and R. Rom, "Shortest-Path and Minimum-Delay Algorithms in Networks with Time-Dependent Edge-Length," *Journal of the Association for Computing Machinery*, vol. 37, no. 3, pp. 607–625, 1990.

[12] P. J. Schneider and D. H. Eberly, *Geometric Tools for 3D Graphics*. San Francisco: Morgan Kaufmann Publishers, 2003.

[13] M. Hall, E. Frank, G. Holmes, B. Pfahringer, P. Reutemann, and I. H. Witten, "The weka data mining software: an update," *SIGKDD Explor. Newsl.*, vol. 11, pp. 10–18, Nov. 2009.